CODES AND STANDARDS ENHANCEMENT INITIATIVE (CASE)

Residential Roof Envelope Measures

2013 California Building Energy Efficiency Standards

California Utilities Statewide Codes and Standards Team October 2011

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Table of Contents

Table of Figures

1. Purpose

This report describes the methodology and results to evaluate a number of measures for vented attics. This report covers the following measures:

1. Reduce heat gain through the roof assembly – this measure evaluated the feasibility and cost-effectiveness of roof deck insulation and cool roofs to reduce the heat gain to the attic space.
2. Increase duct insulation levels – this measure analyzed the cost effectiveness of increasing duct insulation levels from R-4.2 and R-6 to R-8 for all climate zones.
3. Raised heel truss – investigated the cost effectiveness of using a raised heel truss to allow full depth of insulation out to the edge of the ceiling cavity

It should be noted that this proposal is not recommending any changes to duct leakage; however, with the addition of below deck insulation, a radiant barrier will not be required.

This report also describes the methodology to develop an alternate prescriptive option for ducts in conditioned spaces as an alternative to the measures above. As described in more detail later in this report, ducts in conditioned space can be achieved by multiple methods:

a. Vented or unvented cathedral ceiling
b. Placing ducts below a scissor truss with insulation on the bottom rafters of the scissor truss
c. Placing ducts in chases below the dropped ceiling along with the HVAC equipment
d. Placing HVAC equipment in insulated cabinets and ducts in chases below the ceiling or inside walls

The report also describes the methodology for a compliance option for ducts in conditioned space, which places the primary insulation layer at the roof and requires sealing of all openings to prevent infiltration of hot and cold air into the attic space. This effectively places ducts inside conditioned space. Since this is not a common construction in California, this was evaluated as a compliance option: the annual TDV energy use of the cathedralized attic was compared with the TDV energy use of the vented attic prescriptive package.

2. Overview

a. Measure Title	Enhanced roof envelope requirements for vented attics
b. Description	This measure would increase the stringency of building envelope requirements by requiring additional insulation at the roof deck, a higher solar reflectance cool roof, and for some climate zones a raised heel truss to allow the full depth of insulation to be installed out to the top plate. The measure would apply to all residential construction in California. A second related measure is to prescriptively require ducts in conditioned space as an alternative to the above. A third related measure is a provision for unvented attics as a compliance option. This would not be a prescriptive requirement but would give the building community greater flexibility in meeting the Standards.

<table>
<tr><td>c. Type of Change</td><td>
The proposed change for vented attics would likely become a prescriptive requirement. The unvented attic measure would become a compliance option for the Standards and possibly the Reach code. The raised heel truss measure would modify existing Joint Appendix 4 tables for wood-framed attic roofs.

Mandatory Measure – CEC staff has proposed an increase in the mandatory roof insulation requirements from R-19 to R-30. This measure is not addressing mandatory requirements; however, this change would restrict the tradeoffs allowed under the performance approach.

Prescriptive Requirement – Roof deck insulation and raised heel trusses would be a prescriptive requirement. The raised heel truss requirement would only apply in some climate zones.

Compliance Option -Increased cool roof requirements may become a compliance option, an alternate package to the vented attic package. However, a very high solar reflectance (0.7) is needed to equal the benefit of the below deck insulation recommended in the vented attic package.

Modeling – This measure does not affect how the building is modeled.

Other – This change would modify the Joint Appendix 4 (JA4) table for residential wood framed attics, adjusting the existing ceiling insulation U-values for standard (non-raised) trusses to be higher to account for insulation compression at the perimeter, and establish a corresponding set of U-factors for raised heel trusses.
For the Standards documents, the residential compliance packages (currently D and E, but may become a single Package A) would be modified to include the roof deck insulation and raised heel truss requirements. The wood-framed attic roof in Reference Appendix JA4 would be modified to include new U-factors for raised heel trusses and to de-rate the existing U-factors for the default case (no raised heel truss). The base case (reference home) ceiling U-factor in Residential ACM would be reset based upon a raised heel truss.

<table>
<tr><th>Measure</th><th>Applicable Climate Zones</th><th>Type of Change</th><th>Documents Affected</th></tr>
<tr><td>Roof Solar reflectance of 0.24</td><td>All except 1, 2, 3 and 5</td><td>Prescriptive Requirement</td><td>Standards Section 151</td></tr>
<tr><td>Below Deck Insulation</td><td>All except 1, 3 and 5</td><td>Prescriptive Requirement</td><td>Standards Section 151</td></tr>
<tr><td>Raised Heel Truss</td><td>11 through 16</td><td>Prescriptive Requirement</td><td>Standards Section 151, Reference Appendix JA4</td></tr>
<tr><td>Roof Solar reflectance of 0.70</td><td>All except 1, 2, 3 and 5</td><td>Compliance Option</td><td>Standards</td></tr>
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</td></tr>
</table>

<table>
<tr><td>d. Energy Benefits</td><td>

The proposed measure saves both cooling energy and heating energy in most California climate zones. TDV energy savings of approximately 7-10% are expected. The measure also reduces peak demand slightly. The energy savings are calculated by running hourly MICROPAS 2013.b simulations and comparing the new house that includes the proposed vented attic package with the baseline building. *Note that the performance of the baseline building is degraded slightly*, due to the new U-factors calculated with compressed insulation near the eaves. The tables below show the electricity, gas and TDV energy savings for the 2,700 ft^2 prototype house with shingle roof model. The energy savings varies considerably by climate zone.

The vented attic package includes the following:

1) Roof solar reflectance of 0.24 for all climate zones except 1, 2, 3 and 5
2) R-13 below deck insulation for all climate zones except 1 and 5

Energy Saving Summary, 2,700 ft2 Prototype with Asphalt Shingle Roof

	Electricity Savings	Demand Savings (kW)	Natural Gas Savings	TDV Electricity Savings	TDV Gas Savings
Climate Zone	(kWh/yr)	kW	(Therms/yr)	$kTDV/ft^2$-yr	$kTDV/ft^2$-yr
1	0	0	0	0	0
2	178	0.29	24.9	4.29	1.88
3	0	0	0	0	0
4	234	0.35	32.22	4.37	2.43
5	0	0	0	0	0
6	365	0.54	13.96	6.62	1.08
7	235	0.39	5.31	5.08	0.41
8	361	0.46	12.07	5.78	0.93
9	479	0.52	15.03	7.09	1.13
10	404	0.58	20.61	7.58	1.51
11	609	0.65	33.38	9.96	2.44
12	374	0.5	34.51	7.3	2.53
13	706	0.69	30.36	10.75	2.24
14	490	0.61	33.14	8.55	2.43
15	1206	0.74	5.39	14.45	0.41
16	306	0.62	54.22	8.42	4

</td></tr>
</table>

d. Energy Benefits (cont.)	The results for the 2,700 ft^2 prototype house with the tile roof are shown below. The energy savings are slightly lower for this prototype than for the house with the shingle roof. The energy use of the house with the tile roof is slightly lower than the energy use of the house with the asphalt roof, due to the increased mass of the tile roof and the air gap between the tile and roof deck (an R-value of 0.85). The vented attic package includes the following: 1) Roof solar reflectance of 0.24 for all climate zones except 1, 2, 3 and 5 2) R-13 below deck insulation for all climate zones except 1 and 5

Energy Saving Summary, 2,700 ft^2 Prototype with Tile Roof

	Electricity Savings	Demand Savings (kW)	Natural Gas Savings	TDV Electricity Savings	TDV Gas Savings
Units	(kWh/yr)	kW	(Therms/yr)	kTDV/ft^2-yr	kTDV/ft^2-yr
CZ1	0	0	0	0	0
CZ2	140	0.23	20.76	3.33	1.57
CZ3	0	0	0	0	0
CZ4	176	0.25	30.93	3.11	2.33
CZ5	0	0	0	0	0
CZ6	278	0.41	13.6	4.91	1.05
CZ7	179	0.3	5.05	3.93	0.39
CZ8	274	0.35	11.6	4.37	0.89
CZ9	369	0.4	14.64	5.42	1.10
CZ10	408	0.55	17.31	7.23	1.26
CZ11	617	0.62	28.81	9.76	2.11
CZ12	384	0.5	29.81	7.31	2.18
CZ13	715	0.66	26.35	10.61	1.95
CZ14	484	0.58	28.37	8.18	2.08
CZ15	1199	0.7	4.45	14.03	0.34
CZ16	353	0.48	48.4	6.41	3.58

More details on the methodology can be found in the Methodology and Results section.

The savings from this/these measures results in the following statewide first year savings:

Total Electric Energy Savings (GWh)	Total Gas Energy Savings (MMtherms)
37.9	1.86

d. Energy	The statewide impact for single-family and multi-family low-rise is shown below.

Benefits (cont.)

Single Family

	Electricity Savings	Natural Gas Savings	TDV Electricity Savings (PV $)	TDV Gas Savings
Units	(GWh/yr)	(MTherms/yr)	PV $	PV $
CZ1	0	0	$0	$0
CZ2	0.165	0.024	$1,827,646	$861,683
CZ3	0	0.000	$0	$0
CZ4	0.473	0.083	$3,904,807	$2,925,466
CZ5	0	0.000	$0	$0
CZ6	0.330	0.016	$2,724,632	$582,661
CZ7	0.386	0.011	$3,961,447	$393,121
CZ8	0.539	0.023	$4,013,052	$817,304
CZ9	0.837	0.033	$5,744,386	$1,165,835
CZ10	3.610	0.153	$29,880,873	$5,207,455
CZ11	1.992	0.093	$14,716,116	$3,181,455
CZ12	3.754	0.291	$33,383,576	$9,955,704
CZ13	4.946	0.182	$34,280,175	$6,300,315
CZ14	0.793	0.046	$6,262,419	$1,592,400
CZ15	2.308	0.009	$12,615,320	$305,717
CZ16	0.530	0.073	$4,491,167	$2,508,327

Multi-Family Low-Rise

	Electricity Savings	Natural Gas Savings	TDV Electricity Savings	TDV Gas Savings
Units	(kWh/yr)	(Therms/yr)	PV $	PV $
CZ1	0	0	$0	$0
CZ2	0.230	0.034	$2,742,557	$501,609
CZ3	0.000	0.000	$0	$0
CZ4	0.260	0.046	$2,306,728	$670,419
CZ5	0.000	0.000	$0	$0
CZ6	0.835	0.041	$7,401,865	$614,050
CZ7	0.821	0.023	$9,047,650	$348,307
CZ8	1.071	0.045	$8,571,520	$677,206
CZ9	1.759	0.070	$12,960,862	$1,020,427
CZ10	2.590	0.110	$23,026,043	$1,556,704
CZ11	1.214	0.057	$9,636,493	$808,176
CZ12	1.995	0.155	$19,055,951	$2,204,572
CZ13	3.012	0.111	$22,420,632	$1,598,533
CZ14	0.843	0.049	$7,150,646	$705,358

CZ15	2.152	0.008	$12,636,145	$118,793
CZ16	0.494	0.068	$4,499,683	$974,903

Total Statewide Impact

	Electricity Savings	Natural Gas Savings	TDV Savings
Units	(GWh/yr)	(MTherms/yr)	PV millions $
CZ1	0	0	0.00
CZ2	0.394	0.058	5.93
CZ3	0.000	0.000	0.00
CZ4	0.733	0.129	9.81
CZ5	0.000	0.000	0.00
CZ6	1.166	0.057	11.32
CZ7	1.208	0.034	13.75
CZ8	1.610	0.068	14.08
CZ9	2.596	0.103	20.89
CZ10	6.200	0.263	59.67
CZ11	3.206	0.150	28.34
CZ12	5.750	0.446	64.60
CZ13	7.957	0.293	64.60
CZ14	1.637	0.096	15.71
CZ15	4.461	0.017	25.68
CZ16	1.023	0.140	12.47
Total	37.940	1.855	346.86

e. Non-Energy Benefits	Cool roofs will reduce diurnal temperature variations in the roof surface, which can improve the longevity of roofing components. The raised heel truss will eliminate ice dams in cold climate zones (climate zone 16).

f. Environmental Impact

This measure would require additional material (insulation) to be installed at the roof deck; typically this requirement would be met with R-13 unfaced fiberglass batts. The environmental impact is the increased use of polyester resin or some other plastic as a binding agent. According to the EPA, binding agents for fiberglass insulation are 5% by weight.

Material Increase (I), Decrease (D), or No Change (NC): (All units are lbs/year)

	Mercury	Lead	Copper	Steel	Plastic	Others (Indentify)
Per Unit Measure[1]	NC	NC	NC	NC	0.0146	NC
Per Prototype Building[2]	NC	NC	NC	NC	21.15	NC

1. Specify the type of unit such as per lamp, per luminaire, per chiller, etc.
2. For description of prototype buildings refer to Methodology section below.

Water Consumption:
No onsite water savings or increase is expected from this measure.

	On-Site (Not at the Power plant) Water Savings (or Increase) (Gallons/Year)
Per Unit Measure[1]	No Change
Per Prototype Building[2]	No Change

1. Specify the type of unit such as per lamp, per luminaire, per chiller, etc.
2. For description of prototype buildings refer to Methodology section below.

Water Quality Impacts:
Comment on the potential increase (I), decrease (D), or no change (NC) in contamination compared to the base case assumption, including but not limited to: mineralization (calcium, boron, and salts), algae or bacterial buildup, and corrosives as a result of PH change.

	Mineralization (calcium, boron, and salts)	Algae or Bacterial Buildup	Corrosives as a Result of PH Change	Others
Impact (I, D, or NC)	NC	NC	NC	
Comment on reasons for your impact assessment				

g. Technology Measures	Roof deck insulation: below deck insulation options include closed-cell spray foam insulation and fiberglass batts. A separate investigation by Building Science Corporation (BSC) assessed the potential for moisture issues with a number of roof assemblies. The report by the subcontractor is expected to be completed prior to the rulemaking. A number of manufacturers can supply either product. Both deck insulation options are readily available. Cool roofs: several manufacturers of roofing tile make solar reflectance products in a variety of colors with solar reflectance of 0.35 to 0.40. Multiple asphalt shingle manufacturers have products with solar reflectance that meets or exceeds 0.24. See the cool roof section in the main report for a summary of product availability by roofing type. Raised heel truss: all residential truss manufacturers can make raised heel trusses, but very few have been made. Costs would be likely to drop if this were made a prescriptive requirement. **Useful Life, Persistence, and Maintenance:** A cool roof may improve the life of the roof, by reducing the thermal stresses that occur from diurnal temperature variations. To maintain the benefit of a cool roof, periodic cleaning is recommended.
h. Performance Verification of the Proposed Measure	For cool roofs, the primary requirement is certification by the Cool Roof Rating Council (CRRC). For roof deck insulation, no special verification is required, but verification is required if the QII credit is claimed.

i. Cost Effectiveness

The results below are shown for representative climate zones where the measure is cost effective. A range of Present Value (PV) energy cost savings is given. Further details can be found in the Results section of this report. Since it is difficult to estimate future costs, it is assumed that the post-adoption (mature) market costs are the same as the current measure costs. For raised heel trusses, costs may come down slightly with increased market adoption (very few are made in California).

The cost effectiveness calculations below are for a vented attic package that includes:

- Roof solar reflectance of 0.24 for all climate zones except 1, 2, 3, and 5
- Roof deck insulation below the deck of R-13 for all climate zones except 1, 3 and 5

a	b	c		D		e		f	g	
Climate Zone	Measure Life (Years)	Additional Costs[1]– Current Measure Costs (Relative to Basecase) ($)		Additional Cost[2]– Post-Adoption Measure Costs (Relative to Basecase) ($)		PV of Additional[3] Maintenance Costs (Savings) (Relative to Basecase) (PV$)		PV of[4] Energy Cost Savings – Per Proto Building (PV$)	LCC Per Prototype Building ($)	
		Per Unit	Per Proto Building	Per Unit	Per Proto Building	Per Unit	Per Proto Building		(c+e)-f Based on Current Costs	(d+e)-f Based on Post-Adoption Costs
1	30	$0	$0	$0	$0	$0	$0	$0	$0	$0
2	30	$1.30/ft²	$1,885	$1.32/ft²	$1,885	$0	$0	$2,132	($247)	($247)
3	30	$0	$0	$0	$0	$0	$0	$0	$0	$0
4	30	$1.30/ft²	$1,885	$1.32/ft²	$1,885	$0	$0	$2,494	($609)	($609)
5	30	$0	$0	$0	$0	$0	$0	$0	$0	$0
6	30	$1.30/ft²	$1,885	$1.32/ft²	$1,885	$0	$0	$2,799	($914)	($914)
7	30	$1.30/ft²	$1,885	$1.32/ft²	$1,885	$0	$0	$1,885	$0	$0
8	30	$1.30/ft²	$1,885	$1.32/ft²	$1,885	$0	$0	$2,784	($899)	($899)
9	30	$1.30/ft²	$1,885	$1.32/ft²	$1,885	$0	$0	$3,901	($2,016)	($2,016)
10	30	$1.30/ft²	$1,885	$1.32/ft²	$1,885	$0	$0	$3,596	($1,711)	($1,711)
11	30	$1.30/ft²	$2,248	$1.55/ft²	$1885	$0	$0	$4,800	($2,915)	($2,915)
12	30	$1.30/ft²	$2,248	$1.55/ft²	$1885	$0	$0	$4,046	($2,161)	($2,161)
13	30	$1.30/ft²	$2,248	$1.55/ft²	$1,885	$0	$0	$5,322	($3,437)	($3,437)
14	30	$1.30/ft²	$2,248	$1.55/ft²	$1,885	$0	$0	$4,292	($2,407)	($2,407)
15	30	$1.30/ft²	$2,248	$1.55/ft²	$1,885	$0	$0	$6,627	($4,742)	($4,742)
16	30	$1.30/ft²	$2,248	$1.55/ft²	$1,885	$0	$0	$4,684	($2,799)	($2,799)

j. Analysis Tools	TDV energy savings and demand savings were evaluated with the latest research version of MICROPAS, 2013b with the California Simulation Engine (CSE). New U-factors are required to replace existing U-factors for R-30, R-38 and R-49 attic roofs, and new U-factors must be added to JA4 to properly account for the benefit of raised heel trusses. The other measures can be adequately modeled by MICROPAS/CSE.
k. Relationship to Other Measures	This measure will impact other envelope measures directly, and residential non-envelope measures indirectly. Since the proposed measure increases the stringency of the standard design relative to 2008, the energy benefits of other measures will be diminished when interactive effects are considered. This measure (CASE R-2, R-3) incorporates a number of envelope measures together, and the “loading order” of the measures in the rolling basecase affects the cost effectiveness of other measures deemed lower in priority. For instance, a raised heel truss may be cost effective in isolation, but if other roof measures (deck insulation, duct insulation) modify the baseline, the TDV energy benefit of a raised heel truss can be reduced by 50% to 70%.

3. Methodology

For this measure, we used two prototypes that are identical to the 2,700 ft^2 specified by the 2008 Residential ACM Manual, except for two changes. We changed the roof pitch from 5:12 to 4:12 to represent steep-slope roofing, and we modeled both asphalt shingle roofs and tile roofs. All other building inputs for the standard design match the specifications of the 2008 residential ACM manual. See the Appendix for additional details.

3.1 Summary of Measures

This CASE analysis incorporates several measures that impact the roof envelope. The measures may have significant interactive effects. The measures evaluated are summarized below.

<table>
<tr><th>Measure</th><th>Type</th><th>Detail</th></tr>
<tr><td>Higher Solar reflectance Cool Roof</td><td rowspan="4">Vented Attic Package</td><td>Consider increased roof reflectance; single requirement regardless of roof mass</td></tr>
<tr><td>Roof Deck Insulation</td><td>Insulation varies by climate; Maintain existing cool roof requirements</td></tr>
<tr><td>Duct Insulation</td><td>Increase to R-8 in all climate zones; existing cool roof requirements</td></tr>
<tr><td>Raised Heel Truss</td><td>Require RHT; existing cool roof requirements</td></tr>
<tr><td>Increased Attic Insulation</td><td>Prescriptive Requirement</td><td>R-30 to R-38; R-38 to R-49 existing cool roof requirements.</td></tr>
<tr><td>Higher Solar reflectance Cool Roof</td><td>Compliance Option</td><td>Level to be equivalent to vented attic package with roof deck insulation</td></tr>
<tr><td>Ducts in Conditioned Space</td><td>Alternate Prescriptive Measure</td><td>Analyzed late in project as alternative to roof deck insulation</td></tr>
</table>

Figure 1. Measure Summary

3.2 Standalone Measure Methodology

The first step is to evaluate each measure considered as a prescriptive requirement as a standalone measure, without interactive effects. The four measures considered are:

- Below Deck Insulation: add insulation below the roof deck, between the truss members or rafters. Insulation types considered are fiberglass batt or spray foam insulation. Both insulation types are modeled the same way, but the product costs affect the cost effectiveness results. With this measure, it is assumed that a radiant barrier will not be installed on the underside of the trusses, since this is not common practice.

- Raised Heel Truss: install a raised heel truss that allows full depth of insulation out to the perimeter top plate.

- Higher Solar reflectance Cool Roof: increase the required solar reflectance of asphalt shingle to 0.24 (higher values are precluded due to temporary lack of product options) and tile to 0.35-0.40.

- Increased Attic Insulation: increase the amount of blown-in attic insulation to R-38 for temperate climate zones (CZ 1-8) and R-49 for inland and mountain climate zones (CZ9-16).

Each of these four cases is tested relative to a baseline in minimum compliance with the 2008 Title 24 Standards and prescriptive requirements.

The results of this first step will help inform the integrated analysis.

Note that for a revision of this study, ducts in conditioned space (for example, a Cathedralized attic) were evaluated for cost effectiveness. This measure was considered as an alternative to the roof deck insulation package.

3.3 Integrated Analysis Methodology

The next step is to consider the interactive effects between measures, and determine a package of measures that is cost effective. This approach uses a “rolling basecase”, whereby the results of the first measure serve as a starting point for the second measure. The following measures were bundled as a “vented attic package”. In all cases, existing cool roof requirements from the 2008 Standards were maintained.

- Higher Solar reflectance Cool Roof – consider solar reflectance levels that are cost effective as a standalone measure as the starting point in the analysis
- Below Deck Insulation – install either (a) the maximum amount of spray foam insulation that is cost effective, or (b) fiberglass batts below the roof deck.
- Duct Insulation – if cost effective, increase the duct insulation to be R-8 in all climate zones
- Raised Heel Truss

3.4 Compliance Option

The results of the integrated analysis are used to construct one or more compliance options. The TDV energy use of the vented attic package becomes the new energy budget against which other options are compared. For example, a compliance option of a cool roof could be shown to use no more TDV energy than the vented attic package does, for each climate zone. Since the compliance options are alternate methods of compliance and not requirements, cost effectiveness does not need to be shown. The following compliance options are considered:

- Cool roof – determine the equivalent roof solar reflectance required, in lieu of below deck insulation
- Ducts in conditioned space – determine the level of roof deck insulation required for a fully sealed attic at the roof deck to achieve equivalent energy performance. For this option, duct sealing is not required since the ducts are effectively in conditioned space. This can be achieved with an unvented roof or a vented roof.

3.5 Reach Code

For the Reach Code, measures are considered that were not cost effective as prescriptive requirements. The Reach Code includes more aggressive accounting of carbon and other factors in its estimate of time dependent valuation (TDV) of energy. The following measures are considered for Reach:

1. Higher solar reflectance cool roof requirements
2. Unvented attics
3. Increased attic insulation

3.6 Summary of Simulation Test Cases

The tables below summarize the simulations performed for the standalone measure analysis and integrated analysis as described above. MICROPAS Rev 2013.b with the California Simulation Engine (CSE) was used for the simulations. Parametric analyses are run for each test case.

Measure	Primary Variable	Secondary Variable	No of Climate Zones	Total Runs
Below Deck Insulation: SPF	Below R-value: 0, 6, 12, 15, 18, 21	None	16	96
Below Deck Insulation: batts	Below R-value: 0, 13	Mass: Light (shingle), Heavy (tile)	16	32
Cool Roof	Solar reflectance: 0.08, 0.25, 0.40, 0.70	Mass: Light (shingle), Heavy (tile)	16	128
Attic Insulation	Attic JA4 Value: R-30, R-38, R-49	None	16	48
Raised Heel Truss	(same as attic insulation)	None	16	48

Figure 2. Simulations: Standalone Measures

Measure	Primary Variable	Secondary Variable	No of Climate Zones	Total Runs
Below Deck Insulation	Below deck R-value: 0, 13	Roof Mass: Light, Heavy	16	32
Duct Insulation	Duct Insulation: R-4.2, R-6, R-8	Roof Mass: Light, Heavy	13	78
Raised Heel Truss	JA4 Attic U-factor: R-30, R-38, R-49	Roof Mass: Light, Heavy	16	96

Figure 3. Simulations: Integrated Measures

Measure	Primary Variable	Secondary Variable	No of Climate Zones	Total Runs
Cool Roof	Roof Solar reflectance: 0.10, 0.25, 0.40, 0.75	Roof Mass: Heavy	16	64
Ducts in Conditioned Space	Duct System: None	n/a	16	16

Figure 4. Simulations: Compliance Option

The compliance option parametric runs for roof solar reflectance assume a radiant barrier in all climate zones except 1 and 5, and assume a raised heel truss is installed.

3.7 Measure Costs

For each measure, the installed cost was derived from either online survey data, phone surveys, RS Means, or a combination of sources. Detailed cost information and survey results are shown in the Appendix. The Results section shows a summary of measure cost data that was used in the cost effectiveness calculations.

3.8 Measure Cost Effectiveness

Each of the measures evaluated is considered cost effective if the present value of the energy savings over the measure life (30 years) exceeds the first cost of the measure and any additional maintenance costs. The discount rate of 3% is used for the analysis. For integrated measures, the package of measures is considered cost effective if the life cycle cost is reduced as compared to the base case; the present value of the energy savings exceeds the incremental first costs and maintenance costs of the package of measures.

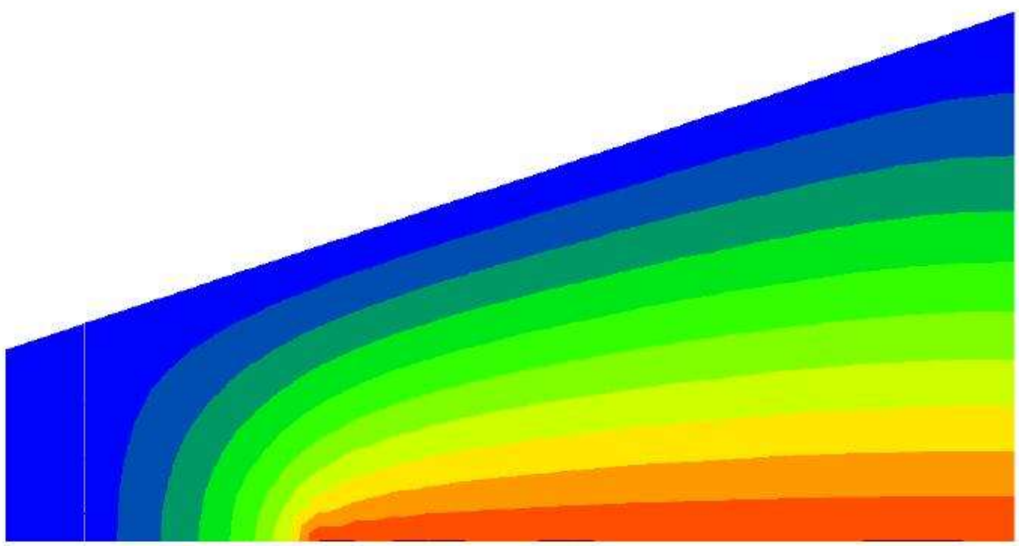
It should be noted that when looking at variables that are essentially continuous (insulation), the insulation level is not chosen to minimize life-cycle cost, but to maximize energy savings while reducing life cycle cost.

For some measures that are not common practice in California, such as a raised heel truss, current costs are used in the analysis. It is possible that costs will come down significantly with widespread adoption, after the technology becomes a prescriptive requirement. A phone survey of truss manufacturers in Wisconsin indicated a lower incremental cost for a raised heel truss with a 12” heel, at 3.6% to 7.5%, compared to a 7% markup in California.

3.9 Adjustment of Roof U-factor for Insulation Compression

Different approaches were considered for estimating the effect of insulation compression on the U-factor of the roof/attic assembly. First, a simple approach using the parallel path method was used. This is the same method used in the current U-factor calculations, and is referenced in the ASHRAE Handbook of Fundamentals. The area where insulation is compressed is calculated based on the roof pitch and depth of attic insulation. For higher insulation R-values, there is a greater area where insulation is compressed, so there is a greater impact on the U-factor.

After some review, an alternate approach was used. With the assistance of Bruce Wilcox, a 2D finite element heat transfer program (FEHT) was used to estimate the U-factor. It was believed that heat does not simply flow in the vertical direction, but rather, a significant portion of heat is transferred through the eaves. The results of the modeling of the attic/roof assembly confirm this assumption.



Temperature plot of steady state finite element heat transfer analysis showing that heat flow is not simply vertical.

Figure 5. Summary Temperature plot of R-30 Attic Roof

A summary of the U-factors used in the analysis are shown below.

Ceiling	2008 JA	Center	6 Foot Truss Edge		Overall		Raised
Insulation R	Table 4.2.1	of Attic	Standard	Raised	Standard	Raised	Savings
30	0.0320	0.0312	0.0345	0.0316	0.0326	0.0313	4%
38	0.0260	0.0249	0.0310	0.0263	0.0276	0.0255	7%
60	0.0170	0.0161	0.0276	0.0200	0.0211	0.0178	16%

Figure 6. Derated Wood-Framed Attic U-factors due to Insulation Compression

These U-factors represent substantially less derating than predicted by a modified version of the parallel path method – see Appendix C. For the parallel path method, a U-factor of 0.0347 was predicted for R-30, and 0.0293 for R-38 and 0.0212 for R-60.

Note that some adjustments to the derated U-factors for R-38 and R-60 were made, due to a proposed requirement that the raised heel be 12” clear to the roof deck so that special blocking is not required.

These U-factors (2D heat transfer column) are recommended as an adjustment to Reference Appendix JA4, and used in the cost effectiveness calculations for a raised heel truss.

3.10 Statewide Savings Estimates

The statewide energy savings associated with the proposed measures will be calculated by multiplying the per unit estimate with the statewide estimate of new construction in 2014. Details on the method and data source of the residential construction forecast are in Appendix F: Statewide Construction Forecast.

4. Analysis and Results

For this research, several measures were evaluated for availability, cost effectiveness and energy savings.

For ***high solar reflectance roofs***, the primary finding is that while higher solar reflectance roofs (solar reflectance of 0.35 to 0.4) are readily available for tile, solar reflectance of shingles is limited to 0.25 to 0.30, and few products exist with an aged solar reflectance greater than 0.24. Rather than provide separate, more stringent requirements for tile roofs, we recommend a single solar reflectance of 0.24, regardless of roofing product, simplifying the prescriptive requirements.
For ***deck insulation*** products, we looked at products for continuous insulation above the roof deck, and a variety of products to be installed below the roof deck, between the truss or framing members. Above deck insulation was limited in application to tile, since shingles require a nailable base, increasing cost and weight. For below deck insulation products, fiberglass batt insulation was much lower in cost than spray foam insulation, allowing it to be cost effective in all cooling climate zones.
Raised heel trusses provide an energy benefit that is greatest with greater depths of attic insulation. Incremental costs of 7% to 9% of truss cost prevent this from being cost effective by itself; however, it is cost effective when considered as part of a vented attic package.
Duct insulation was cost effective in a few climate zones as an isolated measure; however, when considered in combination with below deck insulation, the reduced attic temperatures greatly reduce the heat transfer, reducing the benefits and preventing it from being cost effective.
Higher solar reflectance cool roof was considered as a compliance option; however, a very high solar reflectance is required to provide the same energy benefit as the increased insulation.
Ducts in conditioned space were considered as a compliance option. With the current cost assumptions, the measure is cost effective in all climate zones except climate zone 5. With slightly lower costs the measure would be cost effective in climate zone 5. This is recommended as a compliance option. Other envelope measures and HVAC measures can be added to ensure that this package achieves the same level of energy savings as the Package A.
Unvented attics were considered as an option for compliance and the Reach code; however, the lack of modeling tools prevent us from making any recommendations at this time. This will be considered for Reach Code, provided that the simulation software algorithms are tested.

The recommendation is to modify the prescriptive requirements to increase roof solar reflectance to 0.24 in most climate zones, add a new requirement for R-13 below deck insulation in all climate zones except 1 and 5, and require a raised heel truss in the hotter inland and mountain climate zones (11 through 16). The following section provides details on measure costs, energy benefits, life-cycle cost, measure availability and other practical considerations.

4.1 Measure Cost Summary

A summary of measure costs is presented in the following table. When incremental costs were used, the base case cost assumption is shown. Since cost effectiveness is evaluated relative to the base case, the incremental costs were the ones used in the analysis. For the roof insulation and cool roof measures, costs shown are per square foot of roof area. For duct insulation, incremental costs shown are per square foot of duct surface area. For the 2,700 ft^2 prototype, the residential ACM calculation rules specify a total duct surface area of 743.85 ft^2. For the spray foam insulation, installed costs are

$1.50/ft^2 per inch of foam, with an assumed settled R-value of R-6 per inch, and an additional cost of $0.25/ft^2 to install an ignition barrier to the underside of the foam.

Measure	Base Cost	Cost	Incremental Cost (Y/N)	Source
High solar reflectance shingle (0.24 solar reflectance – compared to 0.08)	$74.70/square $0.747/ft^2	$32/square ($0.32/ft^2)	Yes	Online Survey Data and Phone Survey
High solar reflectance tile (0.35-0.40 solar reflectance – compared to 0.15 solar reflectance)	$130/sqaure ($1.30/ft^2)	$0-$6/square (<$0.06/ft^2)	Yes	Online Survey Data and Phone Survey
R-13 batt deck insulation	n/a	$1.30/ft^2	No	RS Means ($0.65/ft2 from phone survey)
R-6 spray foam insulation	n/a	$1.50/ft^2 + $0.25/ft^2 ignition barrier	No	Phone survey
Additional spray foam insulation	$1.50/ft^2 for R-6 (one inch)	$1.50/ft^2 per inch	Yes	Phone survey
Duct Insulation	$3.04/ft^2 for R-6	$0.595/ft^2 R-6 to R-8 $0.905/ft2 R-4.2 to R-8	Yes	RS Means
Raised Heel Truss	$3.50/ft^2 of projected area cost for a standard truss*	7% for standard heel 9% for high heel	Yes	Online Survey and Phone survey

Figure 7. Measure Cost Summary (details in Appendix)

*Typical value; actual cost may vary for a hip roof or for other roof features

4.2 Standalone Measures

The following measures were first evaluated as “standalone” measures: below deck insulation, higher solar reflectance cool roof, duct insulation and a raised heel truss. For this analysis, each measure was evaluated against a baseline that complies exactly with the 2008 Standards.

4.2.1 Below Deck Insulation

Cost effective analyses of spray foam and fiberglass batt insulation were performed. For below deck insulation, simulations were run for a number of insulation thicknesses ranging from R-0 (none) to R-

21 (3.5”). For polyurethane spray foam insulation, a settled R-value per inch of R-6 was assumed. These results assume no radiant barrier below the spray foam insulation. For batt insulation, it is assumed that R-13 unfaced batts are installed below the deck between the framing members.

Spray Foam Insulation Results

The spray foam costs of \$1.50/ft^2 per inch, and an additional \$0.25/ft^2 for an ignition barrier, are factored into the life-cycle cost calculations. In most climate zones, the incremental energy benefits are outweighed by the cost of the spray foam insulation.
Simulations were run for spray foam insulation levels of 1”, 2”, 2.5”, 3” and 3.5” (with an assumed R-value of R-6 per inch). **Error! Reference source not found.** provides the energy use in kTDV/ ft^2-yr by climate zone for each the insulation thicknesses. Energy use in kTDV/ft^2-yr was converted to a life-cycle energy cost by applying 30-year TDV conversions. The energy cost was added to the installed cost of the insulation to determine the life-cycle cost as shown in **Error! Reference source not found.**.

Climate Zone	Base	R-6	R-12	R-15	R-18	R-21
1	47.31	45.06	44.09	43.78	43.54	43.35
2	57.09	53.94	51.34	50.56	49.99	49.54
3	40.12	36.86	35.71	35.34	35.08	34.88
4	58.56	55.69	52.64	51.71	51.02	50.51
5	38.76	37.28	36.58	36.36	36.2	36.08
6	42.66	37.43	35.52	34.92	34.5	34.17
7	32.63	29.28	27.98	27.58	27.29	27.06
8	53.06	50.75	47.53	46.53	45.81	45.24
9	78.62	74.23	69.82	68.49	67.51	66.75
10	78.92	74.5	70.82	69.72	68.92	68.32
11	118.24	111.74	106.71	105.21	104.11	103.27
12	84.54	79.84	75.6	74.3	73.34	72.61
13	117.21	110.66	105.1	103.42	102.18	101.23
14	106.7	101.61	97.52	96.3	95.4	94.72
15	151.29	143.47	137.3	135.44	134.1	133.06
16	96.31	89.22	86.31	85.32	84.59	84.03

Figure 8. Below Deck Insulation Results, kTDV/ft^2-yr

	Base	R-6	R-12	R-15	R-18	R-21
1	**8.185**	8.758	9.384	9.728	10.083	10.448
2	**9.877**	10.294	10.639	10.901	11.199	11.519
3	**6.941**	7.339	7.935	8.268	8.62	8.982
4	**10.131**	10.597	10.863	11.1	11.377	11.686
5	**6.705**	7.412	8.085	8.444	8.814	9.19
6	**7.38**	7.438	7.902	8.195	8.519	8.86
7	**5.645**	6.028	6.597	6.925	7.272	7.629
8	**9.179**	9.742	9.979	10.204	10.476	10.775
9	**13.601**	13.804	13.836	14.003	14.23	14.496
10	**13.653**	13.851	14.009	14.215	14.474	14.767
11	20.456	20.293	20.218	**20.355**	20.562	20.814
12	**14.625**	14.775	14.836	15.008	15.239	15.51
13	20.277	20.107	19.939	20.046	**20.228**	20.461
14	**18.459**	18.541	18.628	18.814	19.055	19.335
15	26.173	25.783	25.51	25.585	25.75	**25.967**
16	16.662	**16.397**	16.688	16.914	17.185	17.485

Figure 9. Below Deck Insulation Life-Cycle Costs ($/ft^2)

The maximum insulation level was chosen so that the total life-cycle cost does not exceed the LCC of the base case. Spray foam, below deck insulation is not cost effective in climate zones 1-10 and not quite cost effective in climate zones 12 and 14. Spray foam insulation, below deck insulation is cost effective as a standalone measure at the following levels in the following climate zones:

- R-6 cost effective in CZ16 (mountains)
- R-15 cost effective in CZ11 (Red Bluff)
- R-18 cost effective in CZ13 (Fresno)
- R-21 cost effective in CZ15 (Palm Springs)

Figure 10 shows how the incremental energy benefits decrease rapidly as the below deck insulation R-value increases above R-12.
The life-cycle cost is shown graphically for climate zone 11 (Red Bluff) in ***Figure 11***. The results of the spray foam life-cycle costs will be compared against life-cycle cost results from installing fiberglass batt insulation below the roof deck.

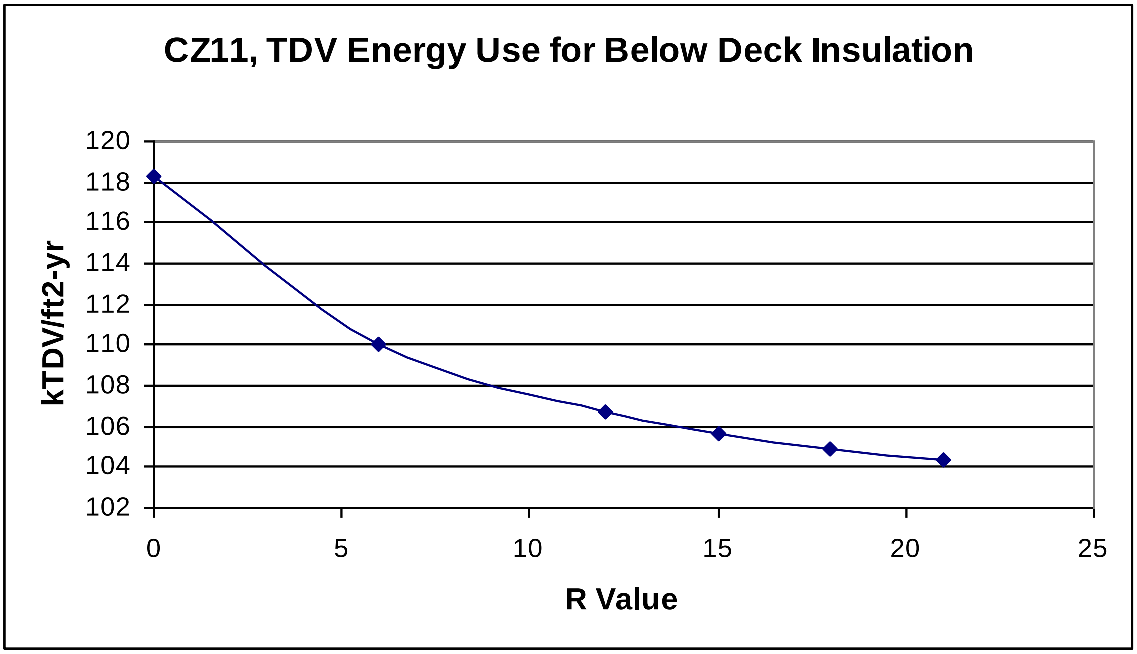


Figure 10. Effect of Below Deck Insulation on Energy Use, CZ11 (Red Bluff)

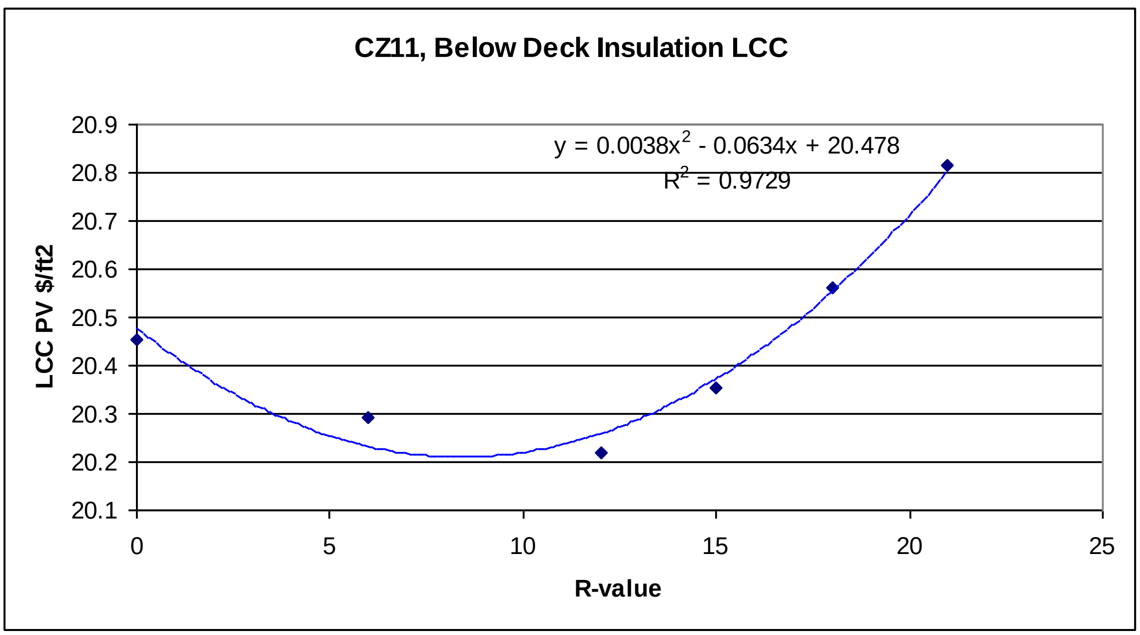


Figure 11. Life-Cycle Cost Analysis ("J" curve) for Below Deck Insulation, CZ11

Fiberglass Batt Insulation Results

For fiberglass batts, the cost effectiveness of an R-13 batt was evaluated for each of the 16 climate zones. Average costs of $1.30/ft^2 were assumed (RS Means and regional markup) as a conservative estimate: a brief phone survey revealed installed costs as low as $0.65/ft^2. The present value of energy savings exceeded the initial costs in every climate except 1 and 5, although only marginally in climate zones 3 (Oakland) and 7 (San Diego), which have little cooling load. Energy simulations were run for both asphalt shingles and tile. The energy savings for a given level of insulation were lower for tile than for asphalt due to the roofing product mass and the resistance of the air gap (modeled as R-0.85 per ACM assumptions). The life-cycle cost tables below are based on a simulation of a house with a tile roof.

The table below first shows the TDV energy use (kTDV/ft^2-yr) for the base case, in exact compliance with the 2008 Standards, and the case with R-13 unfaced batt insulation below the roof deck.

Climate Zone	Base	R-13 below deck	ΔkTDV/ft^2
1	47.31	43.98	3.33
2	57.09	51.05	6.04
3	40.12	35.57	4.55
4	58.56	52.29	6.27
5	38.76	36.5	2.26
6	42.66	35.29	7.37
7	32.63	27.84	4.79
8	53.06	47.15	5.91
9	78.62	69.32	9.3
10	78.92	70.41	8.51
11	118.24	106.14	12.1
12	84.54	75.11	9.43
13	117.21	104.47	12.74
14	106.7	97.06	9.64
15	151.29	136.6	14.69
16	96.31	85.94	10.37

Figure 12. Below Deck Batt Insulation Energy Savings

Climate Zone	LCC Base	LCC R-13	First Cost	Total LCC	Change in LCC $/ft^2
1	$15.24	$14.17	$1.30	$15.47	$0.23
2	$18.39	$16.45	$1.30	$17.75	($0.63)
3	$12.92	$11.46	$1.30	$12.76	($0.16)
4	$18.86	$16.84	$1.30	$18.16	($0.72)
5	$12.49	$11.76	$1.30	$13.06	$0.57
6	$13.74	$11.37	$1.30	$12.67	($1.07)
7	$10.51	$8.97	$1.30	$10.27	($0.24)
8	$17.09	$15.19	$1.30	$16.49	($0.60)
9	$25.33	$22.33	$1.30	$23.61	($1.70)
10	$25.42	$22.68	$1.30	$23.98	($1.44)
11	$38.09	$34.19	$1.30	$35.49	($2.60)
12	$27.23	$24.20	$1.30	$25.50	($1.74)
13	$37.76	$33.65	$1.30	$34.95	($2.80)
14	$34.37	$31.27	$1.30	$32.57	($1.81)
15	$48.74	$44.00	$1.30	$45.30	($3.43)
16	$31.03	$27.68	$1.30	$28.98	($2.05)

Figure 13. Below Deck Batt Insulation Life Cycle Cost Analysis

Note: all costs are in dollars per square foot of roof area

Above Deck Insulation

Although not included in the proposed measures, above deck insulation was considered in the analysis. A set of simulations was performed for selected climate zones to compare the effects of continuous insulation above the roof deck with insulation below the roof deck and between the framing members. The reason that above deck insulation was not considered as a requirement is that although tile can readily adhere to rigid insulation, asphalt shingles require a nailable base. The simulation results showed that R-13 insulation below the roof deck is approximately equal to R-10 of continuous insulation above the roof deck (the exact equivalence varied slightly with climate zone). The performance approach can be used to tradeoff above deck insulation for other required measures.

	Energy Use, kTDV/ft^2-yr		
Climate Zone	R-13 below	R-9 above	R-10 above
6	35.29	35.77	35.53
10	69.88	69.91	69.59
15	136.46	137.05	136.52

Figure 14. Comparison of Below Deck and Above Deck Insulation Performance

4.2.2 High Solar Reflectance Cool Roof

For this measure, increased roof solar reflectance, we first reviewed the availability of high solar reflectance products for a variety of roofing types. The summary graph below shows that higher solar reflectance cool roof options do exist for steep-sloped roofing. Figure 15 shows product availability for several roof types. For tile, a number of products are available with solar reflectance of 0.35 or higher. For asphalt shingle, product availability decreases when aged solar reflectance exceeds 0.25 and no products are available above 0.30. Since the current prescriptive solar reflectance requirement for tile is 0.15, many products are receiving a compliance credit, even though they are standard practice.

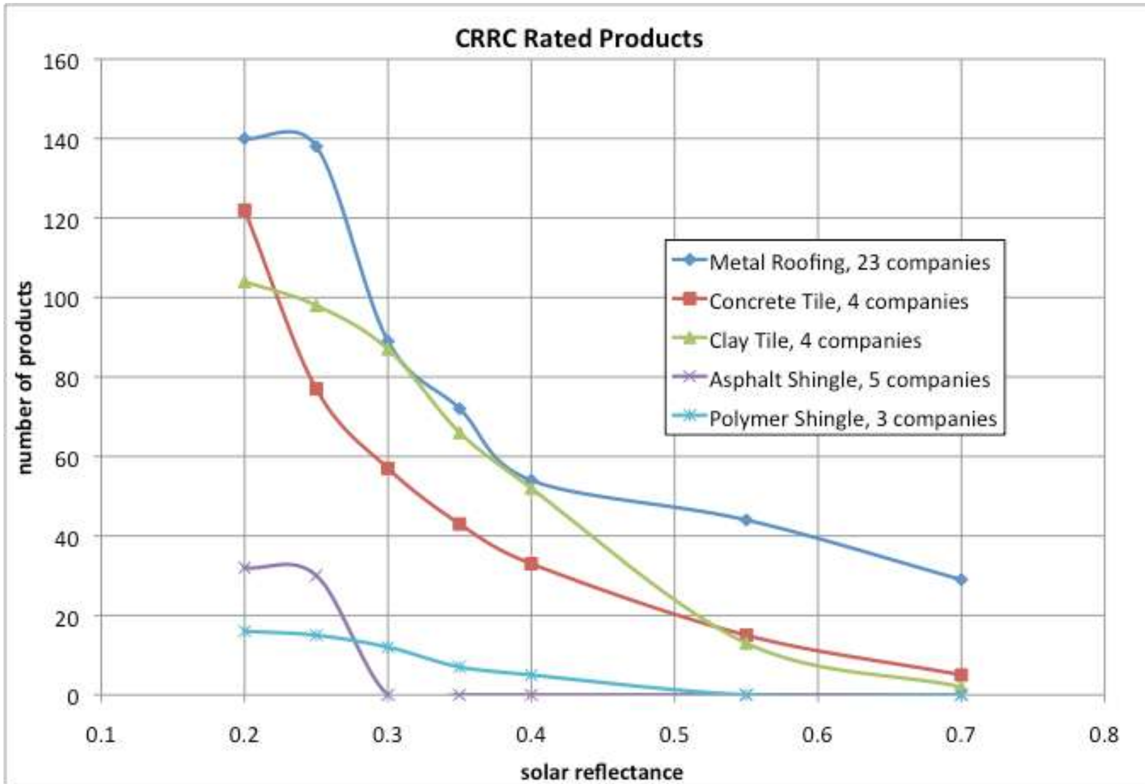


Figure 15. Steep-sloped Roofing Product Availability

Cool roof with an aged solar reflectance of 0.24 was analyzed as a standalone measure, relative to the base case value of 0.08 for asphalt shingle and 0.15 for tile. Simulations were run for a variety of (aged) roof solar reflectance values, for both asphalt and tile roofs. Higher solar reflectance shingle roofs were not considered due to the temporary lack of products with much higher solar reflectance values.

For asphalt shingle, cost effectiveness calculations were run assuming a maximum solar reflectance of 0.24.

The results below show the present value of energy savings in dollars per square foot (1 square of roofing product is 100 ft^2), the incremental cost in dollars per square, and the net present value. The measure is cost effective if its life-cycle cost relative to the base case is less than $0. An asphalt shingle roof with an aged solar reflectance of 0.24 is cost effective in all climate zones except CZ1, 2, 3, and 5.

Climate Zone	kTDV/ft^2 roof	PV \$/ft^2 roof	Cost \$/ft^2 roof	Change in LCC \$/ft^2
1	-1.3	-0.23	0.32	$0.55
2	1.81	0.31	0.32	$0.01
3	1.21	0.21	0.32	$0.11
4	2.77	0.48	0.32	($0.16)
5	-1.43	-0.25	0.32	$0.57
6	3.58	0.62	0.32	($0.30)
7	2.92	0.51	0.32	($0.19)
8	3.82	0.66	0.32	($0.34)
9	5.06	0.88	0.32	($0.56)
10	5.12	0.89	0.32	($0.57)
11	6.05	1.05	0.32	($0.73)
12	4.9	0.85	0.32	($0.53)
13	6.35	1.1	0.32	($0.78)
14	4.79	0.83	0.32	($0.51)
15	8.34	1.44	0.32	($1.12)
16	*4.21*	*0.73*	*0.32*	($0.41)

Figure 16. Cost Effectiveness Calculations, High Solar Reflectance Asphalt Shingle Roof

For tile roofs, a solar reflectance of 0.40 is cost effective in all climate zones except CZ1 (Arcata, North Coast) and CZ 5 (Santa Maria, Central Coast), due to the lack of a cooling load in those climate zones.

The table below shows the TDV energy use (kTDV/ft^2-yr) for different tile roof solar reflectances, and shows the energy savings in terms of square foot of floor area, and square foot of roof area. The savings in the last column (per ft^2 of roof area) are used in the cost effectiveness calculations. Note that while a higher solar reflectance may be cost effective for tile, 0.24 is used in the cost effectiveness calculations.

	kTDV/ft^2-yr				
Climate Zone	Refl=0.15	Refl = 0.24	Refl = 0.40	kTDV/ft^2-yr Savings 0.15 to 0.24	kTDV/ft^2 roof Savings
1	45.45	45.81	46.54	-0.36	-0.670
2	55.59	55.06	54.14	0.53	0.987
3	37.38	37.25	37.05	0.13	0.242
4	56.62	55.92	54.62	0.7	1.303
5	37.6	37.98	38.73	-0.38	-0.708
6	37.97	37.48	36.67	0.49	0.912
7	29.82	29.38	28.59	0.44	0.819
8	52.19	51.19	49.34	1	1.862
9	74.73	73.67	71.65	1.06	1.974
10	81.25	79.83	77.18	1.42	2.644
11	122.62	121.03	118.02	1.59	2.961
12	86.25	84.93	82.36	1.32	2.458
13	121.04	119.38	116.21	1.66	3.091
14	110.88	109.45	106.76	1.43	2.663
15	161.44	159.32	155.22	2.12	3.948
16	*92.59*	*91.81*	*90.37*	*0.78*	1.452

Figure 17. Energy Simulation Results for High Solar Reflectance Tile Roof

The life-cycle cost calculations are shown in the table below.

Climate Zone	Savings, kTDV/ft^2 roof	PV \$/ft^2 roof	Cost/ft^2 roof	Change in LCC, \$/ft^2
1	-0.67	(\$0.12)	\$0.02	\$0.14
2	0.987	\$0.17	\$0.02	(\$0.15)
3	0.242	\$0.04	\$0.02	(\$0.02)
4	1.303	\$0.23	\$0.02	(\$0.21)
5	-0.708	(\$0.12)	\$0.02	\$0.14
6	0.912	\$0.16	\$0.02	(\$0.14)
7	0.819	\$0.14	\$0.02	(\$0.12)
8	1.862	\$0.32	\$0.02	(\$0.30)
9	1.974	\$0.34	\$0.02	(\$0.32)
10	2.644	\$0.46	\$0.02	(\$0.44)
11	2.961	\$0.51	\$0.02	(\$0.49)
12	2.458	\$0.43	\$0.02	(\$0.41)
13	3.091	\$0.53	\$0.02	(\$0.51)
14	2.663	\$0.46	\$0.02	(\$0.44)
15	3.948	\$0.68	\$0.02	(\$0.66)
16	1.452	\$0.25	\$0.02	(\$0.23)

Figure 18. Life Cycle Cost Analysis for Medium Solar Reflectance (0.24) Tile Roof

For a higher reflectance tile roof, the energy savings and the change in life-cycle costs are shown below. The energy savings are much higher than for the medium reflectance (0.24) tile roof. Incremental costs are assumed to be at the high end of surveyed data, \$0.06/ft^2 (\$6.00 per square). The high solar reflectance tile roof is cost effective in all climate zones except 1 and 5, which have no cooling load.

Climate Zone	kTDV/ft^2 Savings 0.15 to 0.40	PV \$/ft^2	Cost \$/ft^2	Change in LCC, \$/ft^2
1	-1.09	(0.35)	0.06	0.41
2	1.45	0.47	0.06	(0.41)
3	0.33	0.11	0.06	(0.05)
4	2	0.64	0.06	(0.58)
5	-1.13	(0.36)	0.06	0.42
6	1.3	0.42	0.06	(0.36)
7	1.23	0.40	0.06	(0.34)
8	2.85	0.92	0.06	(0.86)
9	3.08	0.99	0.06	(0.93)
10	4.07	1.31	0.06	(1.25)
11	4.6	1.48	0.06	(1.42)
12	3.89	1.25	0.06	(1.19)
13	4.83	1.56	0.06	(1.50)
14	4.12	1.33	0.06	(1.27)
15	6.22	2.00	0.06	(1.94)
16	2.22	0.72	0.06	(0.66)

Figure 19. Life Cycle Cost Analysis for High Solar Reflectance (0.40) Tile Roof

4.2.3 Duct Insulation

While not strictly a roof envelope measure, this measure was later added as it impacts heat transfer to the supply air stream. The proposed measure would increase the duct insulation level, if cost effective, to R-8 in all climate zones.

Climate Zone	R-4.2	R-6	R-8	ΔkTDV/ft^2	PV \$/ft^2
1	46.21	45.45	44.96	0.49	0.085
2	56.59	55.59	54.94	0.65	0.112
3	39.48	38.86	38.48	0.38	0.066
4	57.82	56.62	55.85	0.77	0.133
5	38.23	37.6	37.19	0.41	0.071
6	40.87	40.05	39.53	1.34	0.232
7	32.2	31.62	31.26	0.94	0.163
8	52.19	51.22	50.59	1.6	0.277
9	76.08	74.73	73.84	0.89	0.154
10	82.7	81.25	80.32	0.93	0.161
11	124.88	122.62	121.13	1.49	0.258
12	87.99	86.25	85.12	1.13	0.195
13	123.31	121.04	119.53	1.51	0.261

Figure 20. Energy Simulation Results for Increased Duct Insulation

A life cycle cost analysis is shown below. Since the energy savings (dollars per square foot of roof area) and costs (dollars per square foot of duct surface area) are in different units, the life cycle cost and net present value of the measure are shown in terms of dollars for the 2,700 ft^2 prototype. Increased duct insulation as a standalone measure is only cost effective for climate zones 8, 11, 12, and 13.

Climate Zone	PV \$/ft^2 roof	Prototype PV Energy Cost Savings	Incremental Cost \$/ft^2 duct	Prototype Incremental Cost $	Change in LCC
1	0.085	$228.88	0.595	$442.59	$213.71
2	0.112	$303.62	0.595	$442.59	$138.98
3	0.066	$177.50	0.595	$442.59	$265.09
4	0.133	$359.67	0.595	$442.59	$82.92
5	0.071	$191.51	0.595	$442.59	$251.08
6	0.232	$625.91	0.905	$673.18	$47.27
7	0.163	$439.07	0.905	$673.18	$234.11
8	0.277	$747.36	0.905	$673.18	($74.18)
9	0.154	$415.72	0.595	$442.59	$26.87
10	0.161	$434.40	0.595	$442.59	$8.19
11	0.258	$695.98	0.595	$442.59	($253.39)
12	0.195	$527.82	0.595	$442.59	($85.23)
13	0.261	$705.32	0.595	$442.59	($262.73)

Figure 21. Life Cycle Cost Analysis for Increased Duct Insulation

4.2.4 Raised Heel Truss

The raised heel truss measure was evaluated by developing linear correlations between TDV energy use and roof/attic U-factor. Then, the derating procedure was applied to determine the change in U-factor (for an R-30 attic roof and R-38 attic roof) that would result if the insulation were compressed near the eaves. For this measure, both asphalt shingle and tile roofs were analyzed. The results for the tile roof (4:12 roof pitch) are presented. Since the tile roof has a slightly higher solar reflectance and a small insulating effect due to the air gap beneath the tile, the energy benefits of increased insulation are approximately 15% lower for tile than for asphalt shingle.

The slope of the line is proportional to the effect the raised heel truss will have on energy use. The existing insulation level required by code also makes a difference: the thicker the attic insulation required, the greater the area where the insulation will be compressed.
For this measure, the physics of the raised heel truss were not modeled directly. Rather, a two-dimensional finite element heat transfer program was used to calculate a set of U-factors for attic roofs with derating due to insulation compression near the eaves.

The simulations showed a linear correlation between TDV energy use and U-factor. Then, the results of the derating spreadsheet were used to calculate the TDV energy savings.

The correlations of TDV energy use to U-factor are shown below. Using the slope of the lines, the change in energy use can be calculated by:

TDV2 – TDV1 = m (U2 – U1)

Where m is the slope (e.g., 90.113 for CZ1), U2 is the U-factor for a raised heel truss, and U1 is the new calculated U-factor for the Standard design, assuming insulation compression.

This effect was incorporated in the analysis by calculating a U-factor for compressed insulation for different levels of attic insulation (R-30, R-38, R-49, and R-60) corresponding to the entries in Reference Appendix JA4. (These Appendices are available online at the California Energy Commission website at the time of this report.)

For Figure 22, the slope of the line relating TDV energy use to U-factor for climate zone 4 (117.63) is 40% steeper than the slope of the line for climate zone 1 (82.655). This means that for a given change in U-factor, there will be a greater energy benefit for the building in climate zone 4. The greatest energy benefit can be seen in climate zone 15 (slope 203.9) and climate zone 16 (slope 212.37).

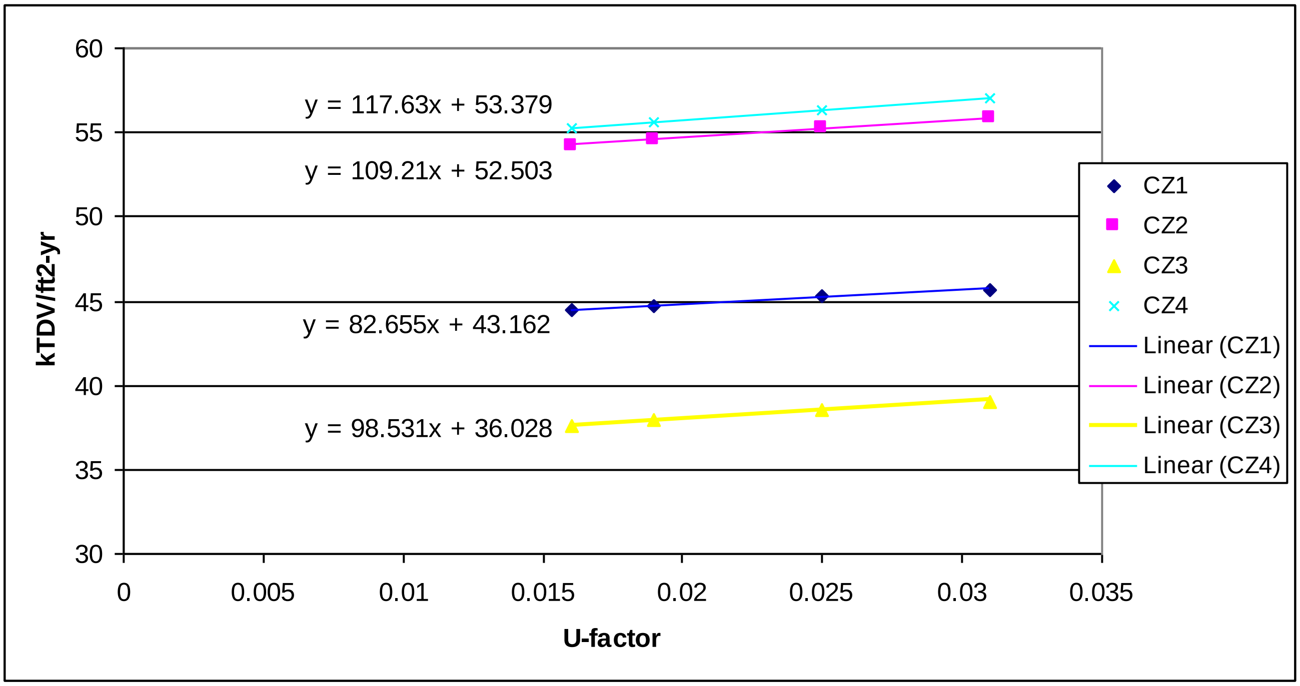


Figure 22. Effect of Roof Insulation on TDV Energy Use, CZ1-4

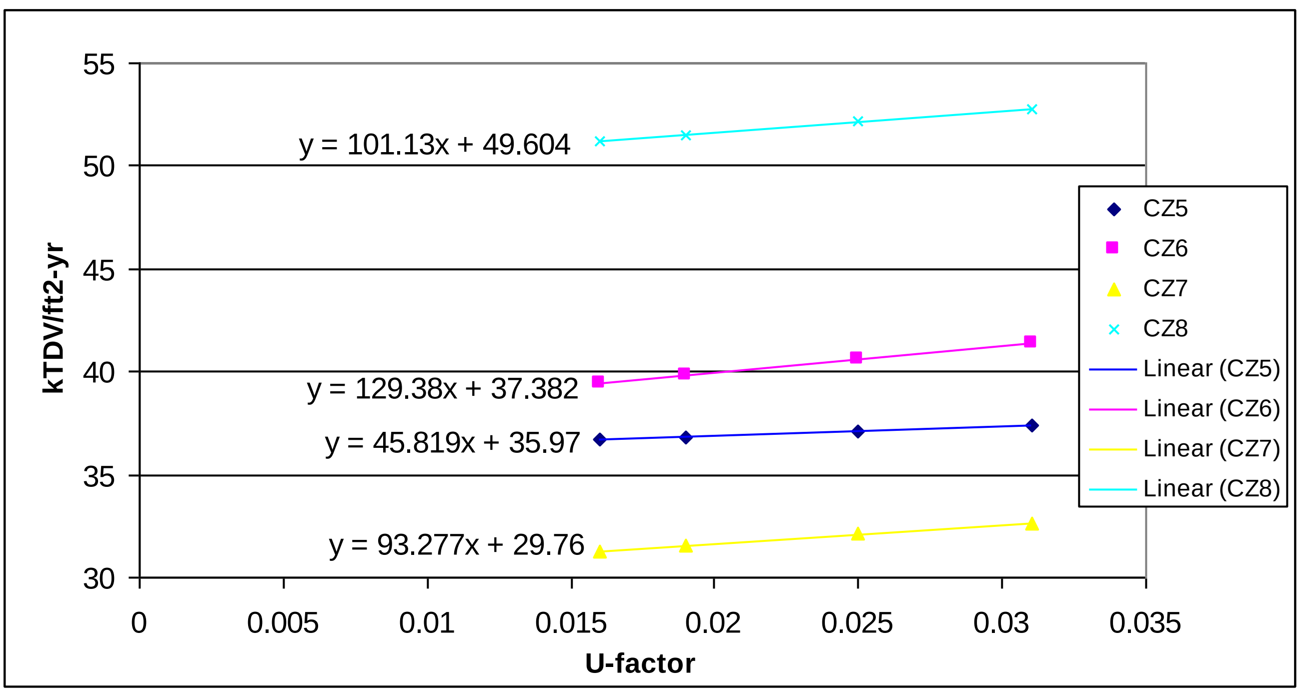


Figure 23. Effect of Roof Insulation on TDV Energy Use, CZ5-8

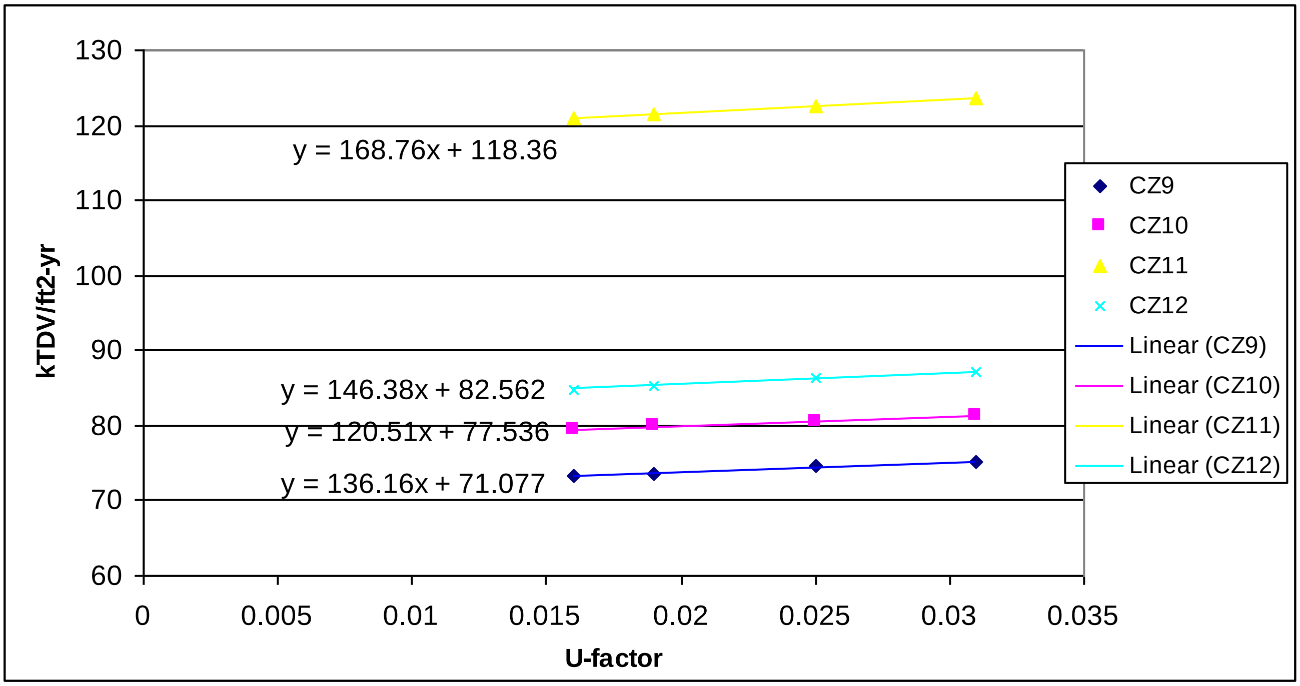


Figure 24. Effect of Roof Insulation on TDV Energy Use, CZ9-12

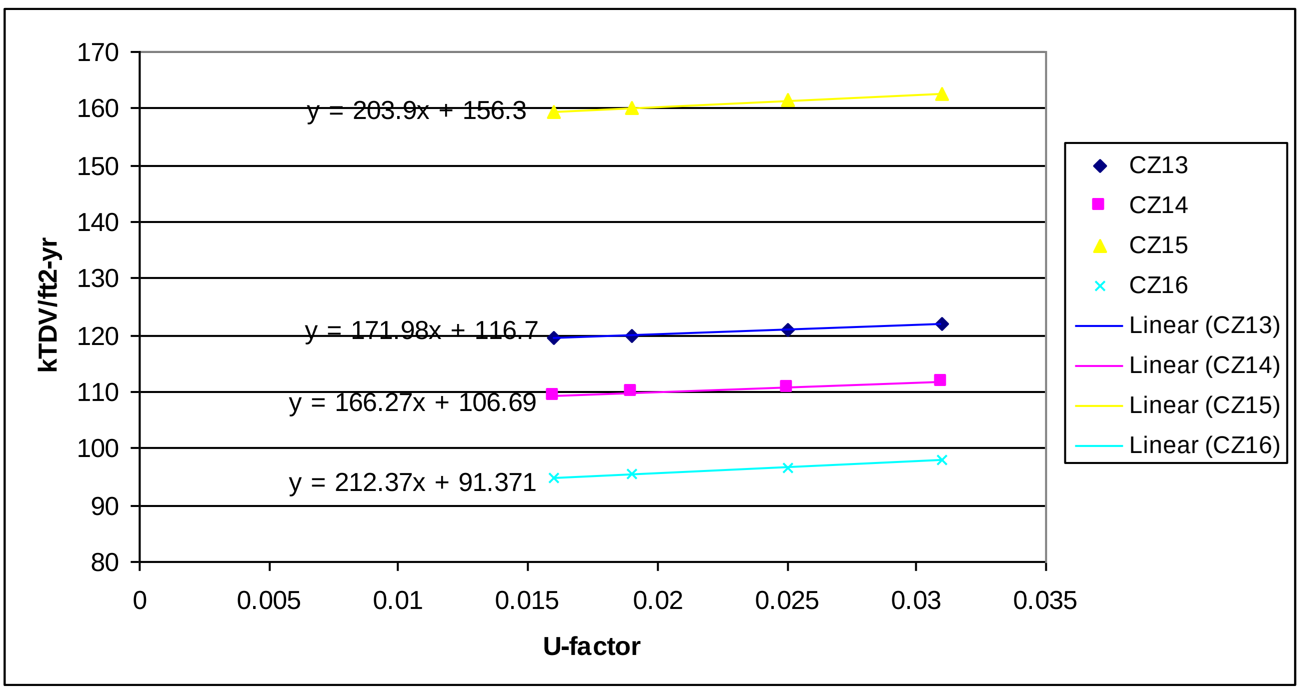


Figure 25. Effect of Roof Insulation on TDV Energy Use, CZ13-16

Different methods were considered for estimating the effects of compressed insulation on the assembly U-factor. Historically, the approach taken is the parallel path method (described in the ASHRAE Handbook of Fundamentals). Initially this approach was used, and was the basis for the results presented at the first stakeholder meeting, April 2011 (see Appendix C). However, a significant amount of heat loss occurs horizontally, near the eaves. To account for this effect, a 2D finite element heat transfer program, FEHT, was used (with the assistance of Bruce Wilcox). The calculations of the area affected by compressed insulation were also revised. As a result, the U-factor degradation was lower than initially calculated. (See **Error! Reference source not found.** for details.)

The table below shows the cost effectiveness calculations for raised heel trusses assuming ceiling insulation levels matching the 2008 prescriptive standards (R-30 for climate zones 2-10 and R-38 for other climate zones). With the revised derating factors for insulation compression, the raised heel truss is not cost effective as a standalone measure. (Initial results from the April 12, 2011 stakeholder meeting showed that the raised heel truss was cost effective for climate zones 11 and 13 through 16.) The incremental cost assumptions are based on an average of survey data, a 7% markup of an average truss cost of \$3.50/ft^2 of projected roof area. A measure is cost effective if its life-cycle cost is less than zero.

Climate Zone	Savings, kTDV/ft^2 Roof	Savings \$/ft^2	RHT Cost \$/ft^2	Change in LCC \$/ft^2
1	0.323	0.056	0.245	0.189
2	0.264	0.046	0.245	0.199
3	0.239	0.041	0.245	0.204
4	0.285	0.049	0.245	0.196
5	0.111	0.019	0.245	0.226
6	0.313	0.054	0.245	0.191
7	0.226	0.039	0.245	0.206
8	0.245	0.042	0.245	0.203
9	0.330	0.057	0.245	0.188
10	0.292	0.050	0.245	0.195
11	0.660	0.114	0.245	0.131
12	0.572	0.099	0.245	0.146
13	0.673	0.116	0.245	0.129
14	0.650	0.112	0.245	0.133
15	0.797	0.138	0.245	0.107
16	0.830	0.144	0.245	0.101

Figure 26. Raised Heel Truss Cost Effectiveness

As a standalone measure, a raised heel truss is not cost effective, but would be cost effective in the inland desert (climate zone 15) and mountain (Climate Zone 16) climate zones if the cost dropped slightly. These results are for the prototype house with a tile roof; the energy savings for an asphalt roof that meets 2008 Standards would be slightly larger, making a raised heel truss cost effective in climate zones 15 (Palm Springs) and 16 (mountains).

4.2.5 Increased Attic Insulation

We also investigated the cost effectiveness of increasing attic insulation, from R-30 to R-38 for temperate climate zones and from R-38 to R-49 for inland valley and mountain climate zones. The results are shown below. RS Means 2010 Building Construction Cost Data was used as the source of cost estimates for blown-in cellulose insulation for this measure. Increasing attic insulation beyond levels required in the 2008 Standards was not cost effective.

Climate Zone	Base R Value	Prop R Value	ΔkTDV/ft^2	Cost Means	PV Sav \$/ft^2	Change in LCC \$/ft^2
1	38	49	0.58	$0.45	$0.10	$0.35
2	30	38	0.7	$0.39	$0.12	$0.27
3	30	38	0.65	$0.39	$0.11	$0.28
4	30	38	0.76	$0.39	$0.13	$0.26
5	30	38	0.3	$0.39	$0.05	$0.34
6	30	38	0.84	$0.39	$0.15	$0.25
7	30	38	0.64	$0.39	$0.11	$0.28
8	30	38	0.63	$0.39	$0.11	$0.28
9	30	38	0.77	$0.39	$0.13	$0.26
10	30	38	0.68	$0.39	$0.12	$0.27
11	38	49	1.03	$0.45	$0.18	$0.27
12	38	49	0.91	$0.45	$0.16	$0.29
13	38	49	1.04	$0.45	$0.18	$0.27
14	38	49	1.09	$0.45	$0.19	$0.26
15	38	49	1.09	$0.45	$0.19	$0.26
16	38	49	1.55	$0.45	$0.27	$0.18

Figure 27. Attic Insulation Cost Effectiveness

4.3 Integrated Analysis

The next step was to test the interactive effects between measures. In this analysis a "rolling base case" approach is used. The cost effectiveness results of the first step serve as the baseline for the second step, and the results of the second step serve as the baseline for the third step. Since the baseline can become more stringent with each step, the incremental energy benefits of subsequent steps are reduced. A vented attic package was evaluated; it includes (if cost effective) a higher solar reflectance roof, insulation below the roof deck, increased duct insulation and a raised heel truss. Below deck insulation of either R-13 fiberglass batts or spray foam insulation was included as the first step. Once the cost effective amount of below deck insulation was determined, the cost effectiveness of increasing the minimum required duct insulation to R-8 was evaluated. Finally, the cost effectiveness of a raised heel truss was evaluated.

4.3.1 First Step: Higher Solar Reflectance Cool Roof

Since a higher solar reflectance cool roof was cost effective for tile in all cooling climate zones (except CZ1 and CZ5), and cost effective for asphalt shingles in all climate zones except the temperate north coast (CZ1, CZ2, CZ3 and CZ5), an aged roof solar reflectance of 0.24 was included in the vented attic package for all climate zones where cost effective. The base case with the higher solar reflectance cool roof was used as the starting point for the next step in the analysis.

4.3.2 Second Step: Below Deck Insulation

Since the analysis of the spray foam insulation and fiberglass insulation showed that the R-13 batt insulation had a lower life-cycle cost than any spray foam option, the R-13 batt was modeled in the integrated analysis. R-13 fiberglass batts have an estimated installed cost of $1.30 per square foot. The SPF insulation is significantly more expensive, at approximately $1.50/ft^2 per inch of foam. An inch of spray foam is assumed to have a settled R value of R-6 per inch. **Error! Reference source not found.** shows the incremental energy savings of below deck insulation by climate zone. The savings are as high as 10% of total TDV energy use in some climate zones.

Climate Zone	Code	R-13	Savings, kTDV/ft^2	kTDV/ft^2 roof
1	47.31	43.98	3.33	6.20
2	57.09	51.05	6.04	11.25
3	40.12	35.57	4.55	8.47
4	58.56	52.29	6.27	11.68
5	38.76	36.5	2.26	4.21
6	42.66	35.29	7.37	13.72
7	32.63	27.84	4.79	8.92
8	53.06	47.15	5.91	11.00
9	78.62	69.32	9.3	17.32
10	78.92	70.41	8.51	15.85
11	118.24	106.14	12.1	22.53
12	84.54	75.11	9.43	17.56
13	117.21	104.47	12.74	23.72
14	106.7	97.06	9.64	17.95
15	151.29	136.6	14.69	27.35
16	96.31	85.94	10.37	19.31

Figure 28. Energy Results, kTDV/ft^2-y, with Below Deck Insulation

The results of the cost effectiveness analysis are shown below. The R-13 batt is cost effective in all climate zones except 1, 3, and 5, and is marginally cost effective in climate zone 7.

Climate Zone	LCC R-0	LCC R-13	LCC $/ft^2	PV Savings $/ft2	Change in LCC $/ft^2
1	15.066	14.126	1.30	0.941	$0.36
2	17.869	16.149	1.30	1.720	($0.42)
3	12.538	11.368	1.30	1.169	$0.13
4	18.259	16.413	1.30	1.846	($0.55)
5	12.396	11.729	1.30	0.667	$0.63
6	13.111	11.098	1.30	2.013	($0.71)
7	10.138	8.769	1.30	1.369	($0.07)
8	16.503	14.664	1.30	1.839	($0.54)
9	24.367	21.638	1.30	2.729	($1.43)
10	25.040	22.343	1.30	2.696	($1.40)
11	37.639	33.773	1.30	3.866	($2.57)
12	26.911	23.832	1.30	3.080	($1.78)
13	37.323	33.190	1.30	4.133	($2.83)
14	33.924	30.883	1.30	3.041	($1.74)
15	48.227	43.482	1.30	4.745	($3.45)
16	*30.249*	*27.520*	*1.30*	*2.729*	($1.43)

Figure 29. Energy Results, kTDV/ft^2-y, with Below Deck Insulation

As shown in the cost effectiveness analysis as a standalone measure, spray foam insulation below the roof deck was only cost effective in climate zones 11, 13, 15, and 16. In contrast, the R-13 fiberglass batt insulation is cost effective in all climate zones except 1 and 5, and is marginally cost effective in climate zones 3 and 7. Therefore, R-13 batt insulation below the roof deck and 0.24 roof solar reflectance are assumed as the starting point for the next step in the analysis.

4.3.3 Third Step: Duct Insulation

The third measure analyzed in the vented attic package is increased duct insulation. The proposal would increase duct insulation to R-8 in all climate zones. Energy simulations were run with duct insulation levels of R-4.2, R-6 and R-8 for climate zones 1 through 13 (climate zones 14, 15 and 16 already have the requirement). The results are shown in the tables below.

For the duct insulation analysis, annual energy use and energy savings are shown per square foot of floor area, and the present value of energy savings is shown per square foot of floor area and in dollars. For costs, since the cost basis is square foot of duct surface area, the costs are shown as total costs for the 2,700 ft^2 house. With the integrated analysis, the energy benefits are reduced considerably with the addition of roof deck insulation. Since the attic temperatures are reduced, the heat transfer to the supply ducts is reduced. **Error! Reference source not found.** shows that the duct insulation incremental savings are outweighed by the costs in all climate zones. While increased duct insulation was cost effective as an isolated measure, its incremental benefits are greatly reduced with the reduced heat gain through the roof assembly.

Climate Zone	Annual Energy Use, kTDV/ft^2-yr		Life Cycle Savings

	R-4.2	R-6	R-8	∆kTDV/ft^2 Roof	PV \$/ft^2	Cost	PV \$	LCC \$
1	47.29	46.57	46.11	0.46	$0.080	$442.59	$214.87	$227.72
2	50.98	50.5	50.17	0.33	$0.057	$442.59	$154.14	$288.45
3	39.66	39.09	38.72	0.37	$0.064	$442.59	$172.83	$269.76
4	52.32	51.66	51.23	0.43	$0.074	$442.59	$200.85	$241.74
5	38.88	38.26	37.88	0.38	$0.066	$442.59	$177.50	$265.09
6	34.92	34.57	34.34	0.58	$0.100	$673.18	$270.92	$402.27
7	31.91	31.28	30.89	1.02	$0.176	$673.18	$476.44	$196.74
8	46.57	46.04	45.7	0.87	$0.151	$673.18	$406.38	$266.81
9	69.26	68.42	67.87	0.55	$0.095	$442.59	$256.90	$185.69
10	106.83	105.78	105.08	0.7	$0.121	$442.59	$326.97	$115.62
11	109.38	108.06	107.19	0.87	$0.151	$442.59	$406.38	$36.21
12	75.36	74.84	74.3	0.54	$0.093	$442.59	$252.23	$190.36
13	105.1	104.06	103.36	0.7	$0.121	$442.59	$326.97	$115.62

Figure 30. Life Cycle Cost Analysis, Increased Duct Insulation

Duct insulation costs are based primarily on 2010 RS Means Building and Construction Data. Duct surface areas are calculated from procedures in the 2008 Residential ACM Manual. For all climate zones, the incremental costs of thicker insulation outweigh the energy benefits, particularly when considered in combination with the below deck insulation. These results are for a tile roof, with R-13 batt insulation below the roof deck in all climate zones except 1, 3, 5, and 7.

The starting point for the next step includes a roof solar reflectance of 0.24, and includes R-13 of below deck insulation for all climate zones except climate zones 1 and 5.

4.3.4 Fourth Step: Raised Heel Truss

The fourth measure considered as part of the vented attic package is the raised heel truss. The results of the second step (cool roof, R-13 batt insulation below the deck, but no increases in duct insulation) were used as the starting point for the analysis. For this measure, a 4:12 roof pitch and tile roof were considered. (With all other building components being equal, the energy benefits of a measure for a tile roof are approximately 15% lower than for an asphalt roof, due to the mass and air space between the tile and roof deck.)
The same procedure that was used in the standalone measure analysis is used here. The slope of the line in the correlation between TDV energy use and U-factor is used, and the “change in U-factor” determined from the finite element heat transfer program results is multiplied by this slope to determine the energy savings from a raised heel truss.

The correlations of TDV energy use to U-factor are shown below. Using the slope of the lines, the change in energy use can be calculated by:

TDV2 – TDV1 = m (U2 – U1)

Where m is the slope (e.g., 90.113 for CZ1), U2 is the U-factor for a raised heel truss, and U1 is the new calculated U-factor for the Standard design, assuming insulation compression.

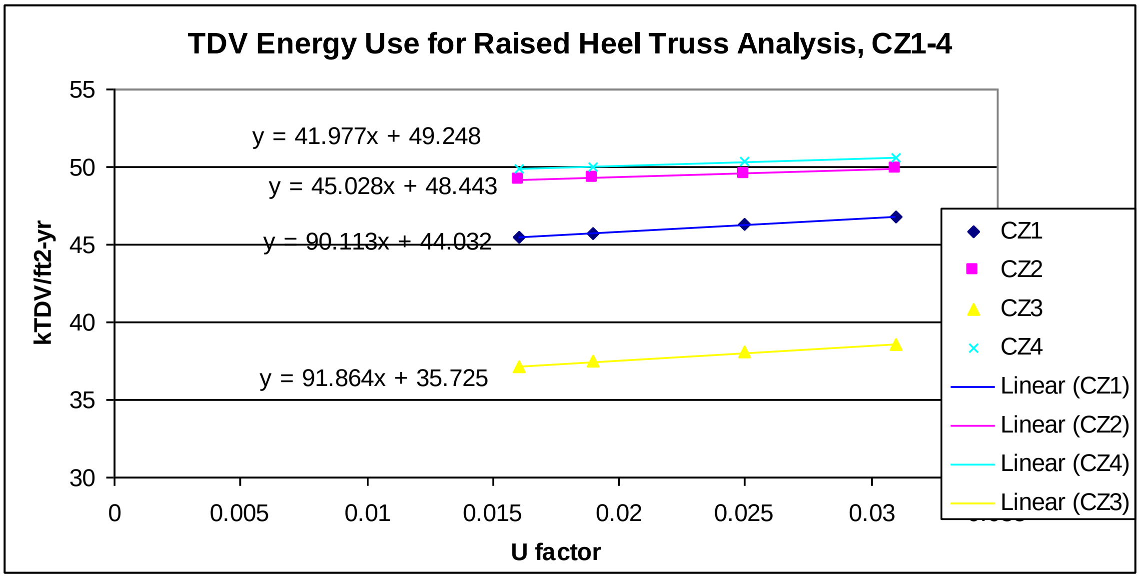


Figure 31. Effect of Roof Insulation, Integrated Analysis, CZ1-4

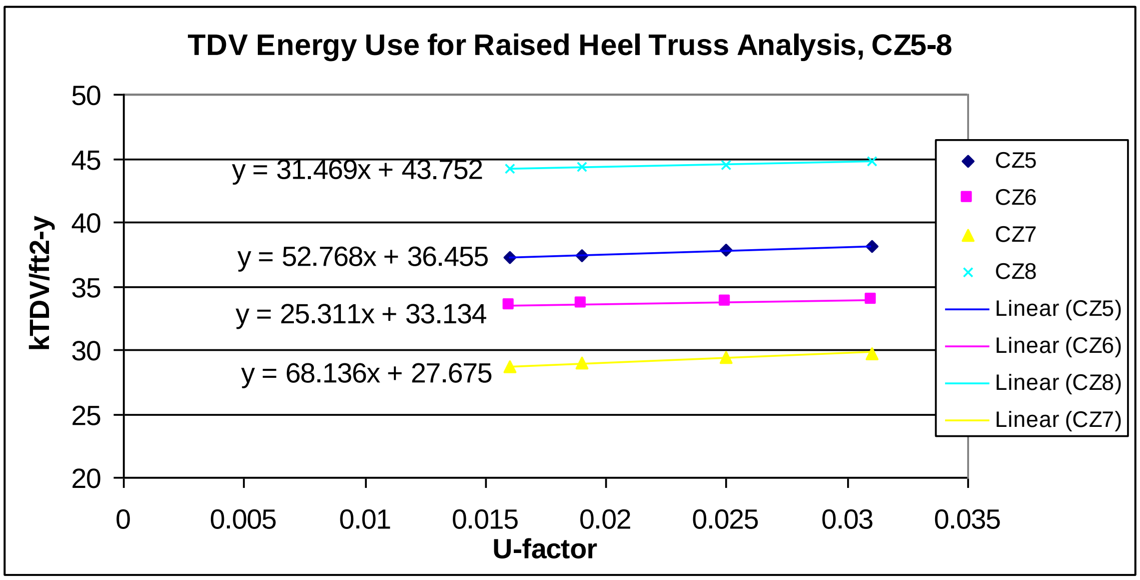


Figure 32. Effect of Roof Insulation, Integrated Analysis, CZ5-8

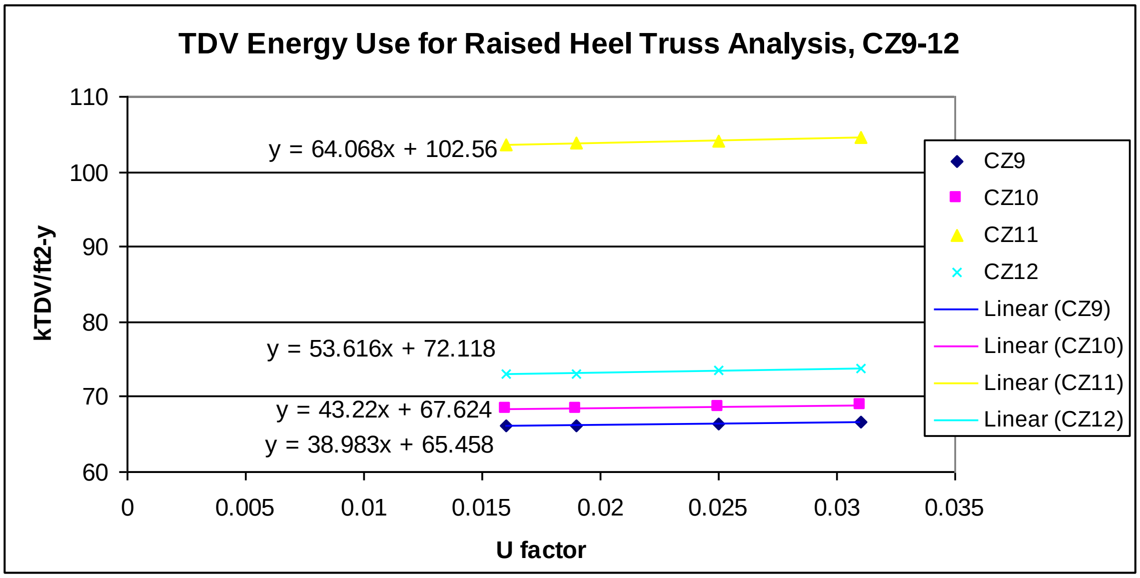


Figure 33. Effect of Roof Insulation, Integrated Analysis, CZ9-12

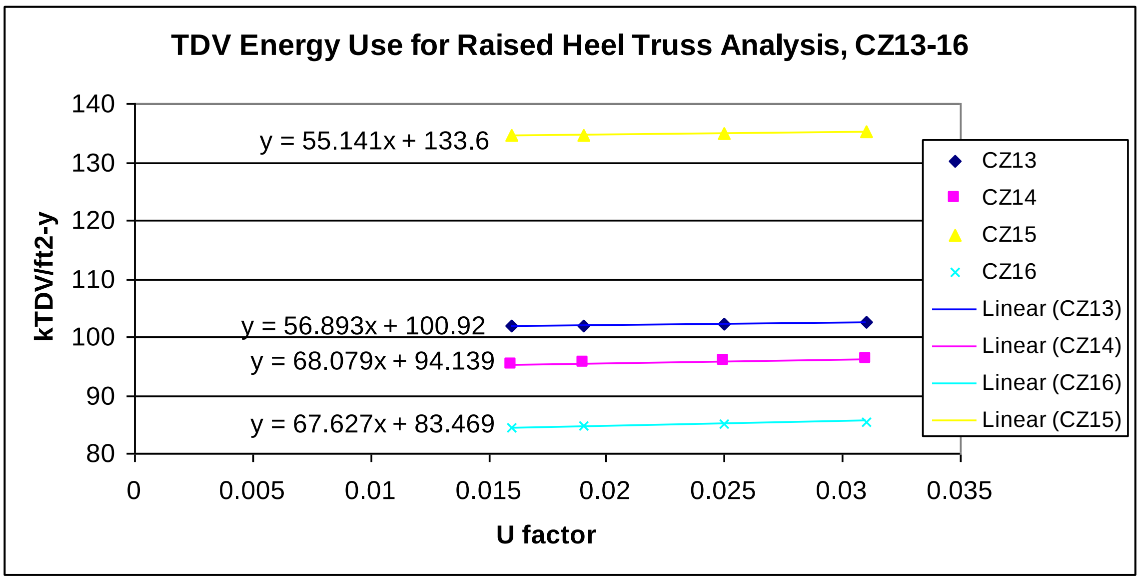


Figure 34. Effect of Roof Insulation, Integrated Analysis, CZ13-16

When the raised heel truss is considered in combination with the other measures (a roof solar reflectance of 0.24, and R-13 below deck insulation), the incremental benefit of a raised heel truss is less than half of the energy benefit of the raised heel truss alone. This reduces the cost effectiveness of the raised heel truss when analyzing the integrated measures. The cost effectiveness results of the raised heel truss are shown in the table below.

Climate Zone	kTDV/ft^2 roof	PV Savings \$/ft^2	RHT Cost \$/ft^2	Change in LCC \$/ft^2
1	0.334	0.058	0.245	0.19
2	0.103	0.018	0.245	0.23
3	0.211	0.037	0.245	0.21
4	0.096	0.017	0.245	0.23
5	0.121	0.021	0.245	0.22
6	0.058	0.010	0.245	0.23
7	0.157	0.027	0.245	0.22
8	0.072	0.013	0.245	0.23
9	0.089	0.015	0.245	0.23
10	0.099	0.017	0.245	0.23
11	0.238	0.041	0.245	0.20
12	0.199	0.034	0.245	0.21
13	0.211	0.037	0.245	0.21
14	0.253	0.044	0.245	0.20
15	0.205	0.035	0.245	0.21
16	0.251	0.043	0.245	0.20

Figure 35. Raised Heel Truss, Incremental Cost/Incremental Benefit Summary

The results show that the addition of a raised heel truss is not cost effective relative to the house that includes below deck insulation. However, for the package of measures as a whole, when we consider the costs and benefits of both below deck insulation and the raised heel truss, the two measures are cost effective in most climate zones relative to the 2008 requirements, as shown in Table 24.

	Present Value of Savings, $/ft² roof			Incremental Cost, $/ft² roof			
Climate Zone	R-13 below Deck ins	Raised heel truss	Package	R-13 below deck	RHT	Package	Change in LCC $/ft² roof
1	0.87	0.058	0.93	$1.30	$0.245	$1.55	$0.62
2	1.47	0.018	1.49	$1.30	$0.245	$1.55	$0.06
3	1.15	0.037	1.19	$1.30	$0.245	$1.55	$0.36
4	1.72	0.017	1.74	$1.30	$0.245	$1.55	-$0.19
5	0.6	0.021	0.62	$1.30	$0.245	$1.55	$0.92
6	1.93	0.010	1.94	$1.30	$0.245	$1.55	-$0.40
7	1.3	0.027	1.33	$1.30	$0.245	$1.55	$0.22
8	1.92	0.013	1.93	$1.30	$0.245	$1.55	-$0.39
9	2.69	0.015	2.71	$1.30	$0.245	$1.55	-$1.16
10	2.48	0.017	2.50	$1.30	$0.245	$1.55	-$0.95
11	3.31	0.041	3.35	$1.30	$0.245	$1.55	-$1.81
12	2.79	0.034	2.82	$1.30	$0.245	$1.55	-$1.28
13	3.67	0.037	3.71	$1.30	$0.245	$1.55	-$2.16
14	2.96	0.044	3.00	$1.30	$0.245	$1.55	-$1.46
15	4.57	0.035	4.61	$1.30	$0.245	$1.55	-$3.06
16	3.23	0.043	3.27	$1.30	$0.245	$1.55	-$1.73

Figure 36. Life Cycle Cost Analysis for Vented Attic Package

A negative life-cycle cost indicates that the package of measures is cost effective. This package is cost effective in climate zones 9 through 16, and is marginally cost effective in climate zones 4, 6 and 8.

Although the raised heel truss is cost effective, when included as part of the vented attic package, it is not cost effective on its own. Moreover, when interactive effects are considered, the incremental energy benefits of a raised heel truss are far outweighed by the costs. While there is some evidence that costs in a mature market are lower, the cost data is not compelling enough to make raised heel trusses a prescriptive requirement. The recommendation is to not include the raised heel truss as part of the prescriptive package, but to consider it for the Reach Code.

4.3.5 Integrated Analysis: Summary

A summary of the integrated analysis is shown below. As the first measure, the integrated result for roof solar reflectance is by definition the same as the standalone result. For below deck insulation, R-13 batt insulation was shown to be cost effective for all climate zones except 1 and 5. The duct insulation measure was cost effective in climate zones 8 and 11 to 13 as a standalone measure, but was not cost effective as an integrated measure. The incremental costs outweighed the incremental benefits, once the increased solar reflectance and below deck insulation were added.

The raised heel truss was not cost effective as a standalone measure; however, when included as part of a package of measures, was cost effective. The recommendation is to include the raised heel truss as a requirement in climate zones 11 through 16, where the energy benefits are greater. The energy benefits of a raised heel truss are greater where R-38 of attic insulation is required, since a greater area of insulation is compressed if no raised heel truss is present.

Measure	**Recommendation Standalone Measure**	**Recommendation Integrated Measure**	**Notes**
Roof Solar Reflectance	0.24 for all climate zones except 1, 2, 3 and 5	Same as standalone	Limited by roofing products available for asphalt shingle
Below Deck Insulation	R-13 for all climate zones except 1, 3 and 5	Same as standalone	R-13 batt insulation chosen over spray foam insulation due to lower life cycle costs
Duct Insulation	R-8 for climate zones 8, and 11 through 16 (current requirement includes 14 through 16)	Not cost effective (keep existing)	Energy benefits reduced considerably with roof deck insulation in place
Raised Heel Truss	Not cost effective	Do not include as prescriptive measure; consider for Reach Code	Only cost effective when bundled with other measures

Figure 37. Summary of Recommendations

The results below are shown for representative climate zones where the measure is cost effective. A range of Present Value (PV) energy cost savings is given. Further details can be found in the Results section of this report. Since it is difficult to estimate future costs, it is assumed that the post-adoption (mature) market costs are the same as the current measure costs. For raised heel trusses, costs may come down slightly with increased market adoption (very few are made in California).

a	b	c		D		e		f	g	
Measure Name	Measure Life (Years)	Additional Costs[1]– Current Measure Costs (Relative to Basecase) ($)		Additional Cost[2]– Post-Adoption Measure Costs (Relative to Basecase) ($)		PV of Additional[3] Maintenance Costs (Savings) (Relative to Basecase) (PV$)		PV of[4] Energy Cost Savings – Per Proto Building (PV$)	Change in LCC Per Prototype Building ($)	
		Per Unit	Per Proto Building	Per Unit	Per Proto Building	Per Unit	Per Proto Building		(c+e)-f Based on Current Costs	(d+e)-f Based on Post-Adoption Costs
Cool roof (shingle)	30	$32/square	$464	$32/sq	$464	$0	$0	$725 to $2088 for CZ6 to CZ16	($261) to ($1,624)	($261) to ($1,624)
Cool roof (tile)	30	$2/square	$29	$2/sq	$29	$0	$0	$4 (CZ3) to $68 (CZ15)	($2) to ($66)	($2) to ($66)
Below Deck Insulation (batt)	30	$1.30/ft^2	$2,039	$1.30/ft^2	$2,039	$0	$0	$2,167 (CZ3) to $6,988 (CZ15)	($128) to ($4,949)	($128) to ($4,949)

Figure 38. Life Cycle Cost Summary by Measure

*Note: with the new U-factor derating from the 2D heat transfer program, the estimated energy benefits of a raised heel truss are reduced. As a standalone measure it is not quite cost effective. However, when combined with the cool roof and below deck insulation, the combination of measures is cost effective as a package.

4.4 Ducts in Conditioned Space

The analysis performed for the June 10th, 2011 IOU stakeholder workshop did not consider ducts in conditioned space. Initially, the scope included consideration of measures such as a cathedralized attic; however, some limitations of the version of modeling software prevented us from accurate results.

For this measure we primarily looked at estimating the energy benefits and approximate costs of placing ducts entirely within conditioned space. This generally involves placing the thermal and air barrier at the roof plane, and providing enough insulation so that the attic becomes part of the conditioned space.

At the stage when this measure was fully investigated, the Title 24 Residential Team had already developed residential package A, which includes roof deck insulation as the primary insulation measure. The ducts in conditioned space is considered as an alternate package; therefore, cost effectiveness need not be proven since there is a cost effective package. However, the high level of savings of this measure, combined with the likely cost effectiveness, demonstrate that this could be included in the prescriptive package. There are some design issues that must be addressed, and these are listed below.

There are several methods of achieving ducts in the conditioned space. Some common strategies employed include a cathedralized attic, dropped ceiling, and a scissor truss (plenum truss). Schematic diagrams of these approaches are shown below in Figures 13 to 15.

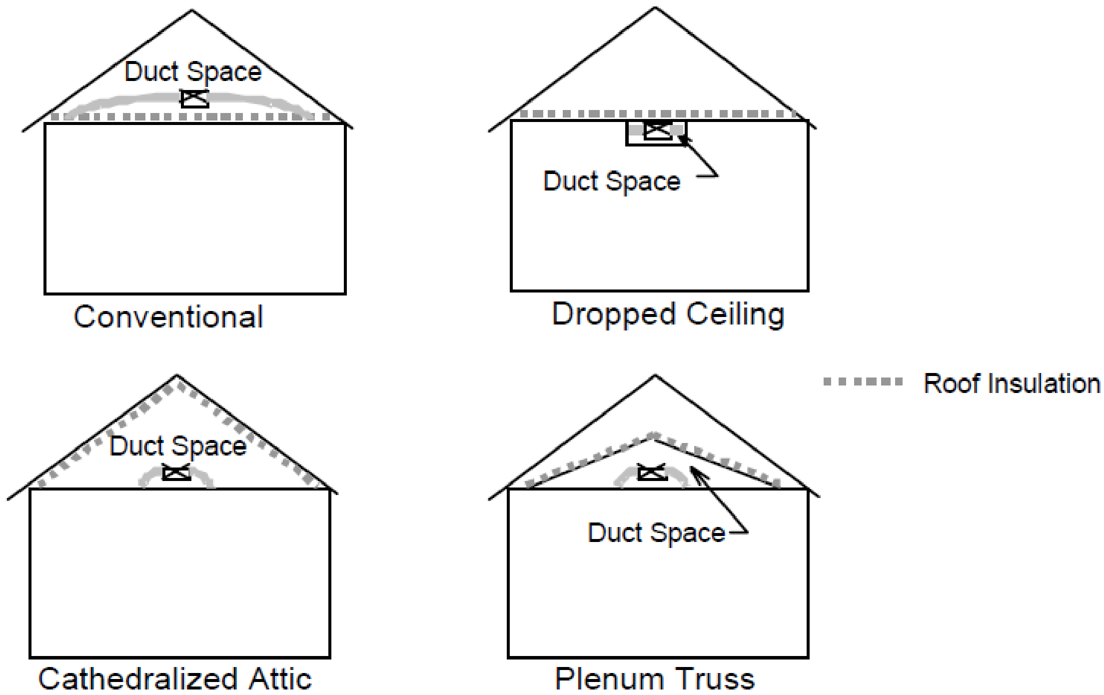


Figure 39. Design Options for Ducts in Conditioned Space

A schematic of a scissor truss is shown in the figure below.

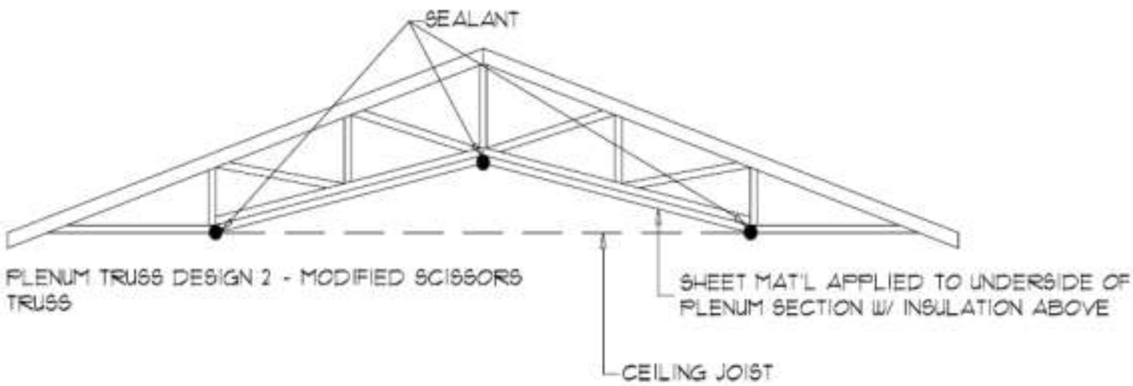


Figure 40. Scissor Truss Schematic

A cathedralized attic involves placing the thermal and air barrier at the roof deck. This can be achieved with either a vented or unvented roof deck. See the figures below for details.

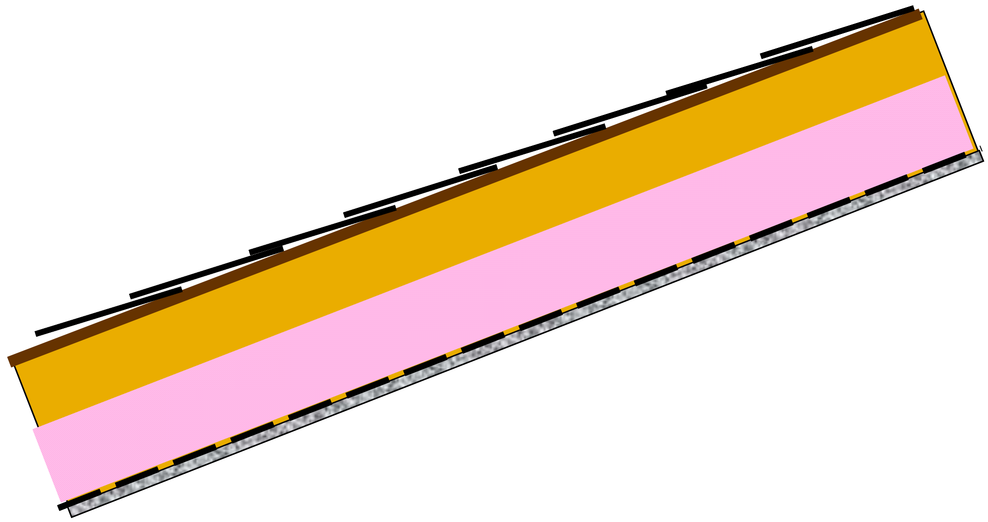


Figure 41. Vented Cathedralized Ceiling

The vented cathedral ceiling provides a 1" air gap between the insulation and the roof deck. With this option a radiant barrier can be installed under the roof deck. The major design changes for the cathedralized ceiling are: installation of netting between framing members to hold insulation, increased insulation area, and air sealing.

The dropped ceiling approach, applicable to spaces with nine to ten foot ceilings, has the advantage of adding framing and an air barrier at the dropped ceiling. Also, a compact duct system can be installed and duct runs can be shorter.

4.4.1 Energy Savings

Ducts in conditioned space was modeled by effectively assuming no duct system. This is done to accurately model this measure because the model assumes return duct leakage as a default. The measure was modeled in each California climate zone.

The energy savings are significant, varying from 9.1% of total TDV energy use in climate zone 5 to 15.4% in climate zone 13 (Fresno), with a maximum absolute energy savings in Palm Springs.

Cost effectiveness is also shown in the table below, and with the current cost estimate, the measure is cost effective in all climate zones except climate zone 5. Cost assumptions are explained in the next section.

CTZ	Std kTDV/ft²	Prop kTDV/ft²	Margin kTDV/ft²	TDV Saving %	Energy Cost Saving $/ft²	PV Energy Cost Savings PV $	Truss Cost $/ft² r	Drywall Cost $/ft² r	Insul-ation Cost $	Total $	BCR
1	44.73	40.06	4.67	10.4%	0.81	$2,181	0.178	0.88	$161	$1,694	1.29
2	56.62	50.07	6.55	11.6%	1.13	$3,060	0.178	0.88	$161	$1,694	1.81
3	39.76	35.75	4.01	10.1%	0.69	$1,873	0.178	0.88	$161	$1,694	1.11
4	57.87	50.67	7.20	12.4%	1.25	$3,363	0.178	0.88	$161	$1,694	1.98
5	36.95	33.60	3.35	9.1%	0.58	$1,565	0.178	0.88	$161	$1,694	0.92
6	42.57	36.73	5.84	13.7%	1.01	$2,728	0.178	0.88	$161	$1,694	1.61
7	33.29	29.24	4.05	12.2%	0.70	$1,892	0.178	0.88	$161	$1,694	1.12
8	53.81	46.46	7.35	13.7%	1.27	$3,433	0.178	0.88	$161	$1,694	2.03
9	76.75	67.23	9.52	12.4%	1.65	$4,447	0.178	0.88	$161	$1,694	2.62
10	82.16	70.73	11.43	13.9%	1.98	$5,339	0.178	0.88	$161	$1,694	3.15
11	123.94	105.06	18.88	15.2%	3.27	$8,819	0.178	0.88	$161	$1,694	5.20
12	87.27	75.15	12.12	13.9%	2.10	$5,661	0.178	0.88	$161	$1,694	3.34
13	122.42	103.52	18.90	15.4%	3.27	$8,828	0.178	0.88	$161	$1,694	5.21
14	111.45	96.52	14.93	13.4%	2.58	$6,974	0.178	0.88	$161	$1,694	4.12
15	162.55	140.82	21.73	13.4%	3.76	$10,150	0.178	0.88	$161	$1,694	5.99
16	97.55	84.17	13.38	13.7%	2.31	$6,250	0.178	0.88	$161	$1,694	3.69

Figure 42. Energy Savings and Life Cycle Cost Analysis for Ducts in Conditioned Space

4.4.2 Measure Costs

For measure costs, we assumed that the scissor truss option would be used. The scissor truss would allow space for ducts in the plenum below, and leave adequate space for insulation. Typically the slope of the bottom chord of a scissor truss is at least half of the slope of the top chord. If the slope of the bottom chord is no greater than 2 in 12, then blown in insulation can be used without settling.

The additional costs considered for this measure were the cost of the trusses themselves, the additional costs of dry wall below the truss, and additional insulation for the sloped surface. A survey of truss manufacturers (Results provided in Appendix A) provided an average estimate of a 5% additional cost for scissor trusses. From previous surveys to manufacturers, a standard roof truss costs $3.55 per square foot of projected roof area. This yields an additional cost of about $0.178/ft^2 for the scissor truss. Unfinished half-inch drywall costs are estimated from RS Means at $0.88/ft^2. Additional insulation costs are estimated at $161 for the house. The total additional cost for the measure for this design option is $1,700 for the house; this cost includes the incremental scissor truss cost, the cost of the drywall and the incremental cost of insulation.

This estimate does not include potential energy savings from not having to verify duct sealing, reduced duct insulation to R-4.2, and a possible savings from downsizing HVAC equipment.

According to sizing results from the simulations, the design cooling load is reduced a half ton to three quarters a ton (6,000 Btu/h to 9,000 Btu/h), which could result in downsized equipment.

CTZ	Base Load (Btu/hr)	Proposed Load (Btu/hr)	Equip Size Base (Btu/hr)	Equip Size Proposed (Btu/hr)	Load Reduction (Tons)	Equipment Reduction (Tons)	Equipment Savings ($)
1	48,808	45,809	60,808	51,809	0.25	0.75	$225
2	45,952	40,578	51,952	46,578	0.45	0.45	$134
3	49,959	44,904	61,959	50,904	0.42	0.92	$276
4	35,389	32,035	41,389	38,035	0.28	0.28	$84
5	34,040	31,092	40,040	37,092	0.25	0.25	$74
6	37,395	33,038	43,395	39,038	0.36	0.36	$109
7	36,000	32,596	42,000	38,596	0.28	0.28	$85
8	39,451	35,754	45,451	41,754	0.31	0.31	$92
9	42,662	38,254	48,662	44,254	0.37	0.37	$110
10	52,424	46,505	64,424	52,505	0.49	0.99	$298
11	52,253	45,864	64,253	51,864	0.53	1.03	$310
12	47,178	41,852	53,178	47,852	0.44	0.44	$133
13	49,279	43,603	61,279	49,603	0.47	0.97	$292
14	56,451	49,535	68,451	61,535	0.58	0.58	$173
15	57,326	49,952	69,326	61,952	0.61	0.61	$184
16	52,310	47,389	64,310	53,389	0.41	0.91	$273

Figure 43. Energy Sizing Results for Ducts in Conditioned Space

Note: sizing estimate above includes ACM allowance of extra half ton for capacity less than or equal to 48,000 Btu/h and extra ton for capacity greater than 48,000 Btu/h

However, there are some additional costs not included in the current estimate. The builder would have to verify that the ductwork and whole house leakage are less than 25 CFM50 to claim ducts in conditioned space. In some cases while it can't be required due to preemption laws, a sealed combustion furnace might be required. A rough estimate of additional cost for the sealed combustion furnace is $400 (Building Science Corporation).

Previous studies done for a PIER research project quote incremental costs as estimated by the builder at approximately $780 for the cathedralized attic and $1500 for the plenum truss[1]. There may be other design options that do not require as significant incremental costs as the one illustrated here. Also, it is important to point out that the present value energy cost savings of ducts in conditioned space for a house in climate zones 10 through 16 is over $5,000, so even a design with higher costs would likely be cost effective.

[1] Hderick, Roger, 2003. Costs & Savings for Houses Built with Ducts in Conditioned Space: Technical Information Report, CEC, October 2003, publication 500-03-082-A-31.

4.4.3 Design Issues

The ducts in conditioned space alternate measure was first presented at a CEC stakeholder pre-rulemaking workshop on August 23. The results were presented and a case was made to include ducts in conditioned space as a prescriptive compliance option at a minimum, or possibly develop a package with ducts in conditioned space that could replace or be an alternative to package A, which includes the roof deck insulation measure. The following design issues were mentioned at the presentation at the August 23 workshop:

- Redesign of current building prototypes
  - Only 2.5 years out
- Limit on types of heating placed in conditioned space
  - Sealed combustion furnace
  - Heat pump
  - Hot water coil in air handler
- What is appropriate energy impact of sealed mechanical room (alternate approach)
  - Two ducts each no less than 3" diameter and with 1 sq inch area per 4,000 Btu/hr.
- Code clarification on allowed/recommended type of cathedral ceiling
  - Vented
  - Unvented (and type of insulation allowed)
  - Does this change by climate zone?

For a sealed combustion furnace, a mechanical closet, such as located adjacent to the garage, would be needed. Additional costs were mentioned above, although the condensing furnaces have a much higher efficiency than conventional furnaces. These types of furnaces require pressure control and are susceptible to pressure differences – in some extreme cases a house exhaust fan turning off or on can cause the furnace vent to trip. A combined hot water heater / space heater is another design option.

For cathedral ceilings, the conditioned attic can be achieved with a fully sealed (unvented) attic, or a vented attic, but still with air sealing below the insulation. The International Residential Code (IRC) typically requires 1" of air space between the insulation and the roof deck, and some shingle manufacturers will not fully warrant their products over an unvented attic. Some studies have suggested that the shingle surface temperature rises only a few degrees F compared to a vented attic; others have suggested a 10% decrease in product life when used with an unvented attic. This remains a subject of controversy. However, there is no requirement for an unvented attic to achieve ducts in conditioned space. A vented attic can be used provided that the thermal and air barrier is at the roof deck.

To confirm that ducts are indeed in conditioned space, an air leakage test is required to verify that the leakage to the outdoors is no greater than 25 cfm at 50 Pa. At this level, special instrumentation that is available is required to confirm that there is no excessive leakage.

4.5 Statewide Savings Estimates

The recommended package saves a significant amount of energy and reduces demand for most climates. Statewide impacts were estimated using the construction estimates documented in Appendix F: Statewide Construction Forecast.

The total electricity and gas savings potential for this measure are 37.94 GWh per year and 1.855 million therms per year. This includes both single-family construction and multi-family low-rise construction. This measure is not applicable to high-rise construction.

5. Recommended Language for the Standards Document, ACM Manuals, and the Reference Appendices

The proposed changes affect the prescriptive standards, alternate component package D[2], and affect Reference Appendix JA4 U-factors in the wood-framed attic roofs table. The roof solar reflectance requirements have been made more stringent, and a new requirement is listed for below deck insulation. The insulation below the roof deck is in addition to existing ceiling insulation requirements. The duct insulation requirements remain the same.

The radiant barrier requirement is removed from the prescriptive standard and replaced with a below deck insulation requirement. The energy benefit of the below deck insulation exceeds that of the radiant barrier, and it is not common practice to install a radiant barrier to the underside of the roof trusses.

Table 151-C Component Package D (Vented Attic Package)

	Climate Zone															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Roof Solar reflectance	NR	NR	NR	0.24	NR	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24
Ceilings	R38	R30	R30	R30	R30	R30	R30	R30	R30	R30	R38	R38	R38	R38	R38	R38
Radiant Barrier	NR	~~REQ~~ NR	NR	~~REQ~~ NR	NR	NR	NR	~~REQ~~ NR	~~REQ~~ NR	~~REQ~~ NR	~~REQ~~ NR	~~REQ~~ NR	~~REQ~~ NR	~~REQ~~ NR	~~REQ~~ NR	NR
Below Deck Insulation	NR	R-13	NR	R-13	NR	R-13	R-13	R-13	R-13	R-13	R-13	R-13	R-13	R-13	R-13	R-13
Duct Insulation*	R-6	R-6	R-6	R-6	R-6	R-4.2	R-4.2	R-4.2	R-6	R-6	R-6	R-6	R-6	R-8	R-8	R-8

The Reference Appendix JA4 table that establishes wood-framed attic roofs is also updated, based on refined U-factor calculation procedures. U-factor can be calculated using the parallel path method or using 2D heat transfer software packages.

The following shows how ducts in conditioned space can be included in the Standards. CEC staff has expressed a desire to move alternate packages to the Reference Appendices.

[2] This may become Package A with the 2013 Standards Update. Also, alternate package descriptions may be moved to the Reference Appendices.

Table RAx – 1 Alternate Component Package for Ducts in Conditioned Space (partial)

	Climate Zone															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Roof Solar reflectance	NR	NR	NR	0.24	NR	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24
Ceilings	R38	R30	R30	R30	R30	R30	R30	R30	R30	R30	R38	R38	R38	R38	R38	R38
Radiant Barrier	NR	~~REQ~~ NR	NR	~~REQ~~ NR	NR	NR	NR	~~REQ~~ NR	~~REQ~~ NR	~~REQ~~ NR	~~REQ~~ NR	~~REQ~~ NR	~~REQ~~ NR	~~REQ~~ NR	~~REQ~~ NR	NR
Below Deck Insulation	R38	R30	R30	R30	R30	R30	R30	R30	R30	R30	R38	R38	R38	R38	R38	R38
Duct Insulation*	R-4.2	R-4.2	R-4.2	R-4.2	R-4.2	R-4.2	R-4.2	R-4.2	R-4.2	R-4.2	R-4.2	R-4.2	R-4.2	R-4.2	R-4.2	R-4.2
(HVAC measures)	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD

Determination of other envelope measures (wall and fenestration) and HVAC measures is outside the scope of this study, but presumably measures included in the standard residential package A could be included here. Duct sealing would not be required, but a duct leakage test would be required, as is currently required in the 2008 Title 24 Residential Standard.

The duct leakage test currently specified in Reference Appendix RA3 would be required to use the ducts in conditioned space package. Additional acceptance test criteria may be required to verify ducts in conditioned space.

The following table would be included to give credit for raised heel trusses, by applying a lower U-factor from Reference Appendix JA4.

Table JA4.2.1 Wood Framed Attic Roofs (DRAFT)

Truss Spacing	R-value of Attic Insulation		Rated R-value of Continuous Insulation1 RHT	None	R-2	R-4	R-6	R-7	R-8	R-10	R-14
			R	A	B	C	D	E	F	G	H
16 in. OC	None	1		0.300	0.187	0.136	0.107	0.097	0.088	0.075	0.058
	R-11	2		0.079	0.068	0.060	0.053	0.051	0.048	0.044	0.037
24 in. OC	None	13	0.305	0.305	0.189	0.137	0.108	0.097	0.089	0.075	0.058
	R-11	14	0.076	0.076	0.066	0.058	0.052	0.050	0.047	0.043	0.037
	R-13	15	0.068	0.068	0.060	0.054	0.048	0.046	0.044	0.041	0.035
	R-19	16	0.048	0.048	0.043	0.040	0.037	0.036	0.034	0.032	0.029
	R-21	17	0.043	TBD	0.040	0.037	0.034	0.033	0.032	0.030	0.027
	R-22	18	0.041	TBD	0.038	0.036	0.033	0.032	0.031	0.029	0.026
	R-25	19	0.037	TBD	0.034	0.032	0.030	0.029	0.028	0.027	0.024
	R-30	20	0.031	0.0337	0.029	0.028	0.026	0.025	0.025	0.024	0.022
	R-38	21	0.025	0.0283	0.024	0.023	0.022	0.021	0.021	0.020	0.018
	R-44	22	0.021	TBD	0.020	0.019	0.019	0.018	0.018	0.017	0.016
	R-49	23	0.019	0.0244	0.019	0.018	0.017	0.017	0.017	0.016	0.015
	R-60	24	0.016	0.0221	0.016	0.015	0.015	0.014	0.014	0.014	0.013

The table above shows adjusted U-factors for the standard truss case for R-30, R-38 and R-60. Adjustments for other attic insulation levels will need to be calculated. The U-factors for continuous insulation in addition to the attic insulation will need to be updated as well, based on the equation for two materials in series. Columns B through H have not yet been updated.

The degraded U-factors for a standard truss have been determined for attic insulation levels R-30, R-38, R-49 and R-60 but need to be determined for the other insulation cases in the table. Also, the U-factors may need to be recalculated due to a desire to have a raised heel truss height of 12 inches to reduce requirements for blocking.

The California Energy Commission has proposed a change for residential roofs, to update the mandatory requirement for ceiling insulation from R-19 to R-30. Since the code prescriptively requires R-30 to R-38 insulation for all climate zones, this level of insulation has already been shown to be cost effective. This change would restrict the building envelope tradeoffs available with the residential performance approach to compliance. The changes to the code language are shown below.

Section 150 – MANDATORY FEATURES AND DEVICES

(a) Ceiling Insulation. The opaque portions of ceilings separating conditioned spaces from unconditioned spaces or ambient air shall meet the requirements if either item (1) or (2) below:

1. Ceilings shall be insulated between wood framing members with insulation resulting in an installed thermal resistance of R-30 or greater for the insulation alone.
   ALTERNATIVE to Section 150(a)1: Insulation which is not penetrated by framing members may meet an R-value equivalent to installing R-30 insulation between wood framing members and accounting for the thermal effects of framing members.
2. The weighted average U-factor of ceilings shall not exceed the U-factor that would result from installing R-30 insulation between wood framing members in the entire ceiling and accounting for the effects of framing members.

Under Section 152, Alterations, code language will be modified to reflect the new prescriptive requirements for roof reflectance and roof deck insulation when the alteration impacts the roof. The removal and changes to exceptions will need to be reviewed with CEC staff. The low slope reflectance requirement matches the CASE proposal for low-sloped nonresidential roofs.

(b) **Alterations.** Alterations to existing residential buildings or alterations in conjunction with a change in building occupancy to a low-rise residential occupancy shall meet either Item 1 or 2 below.

1. **Prescriptive approach.** The altered component and any newly installed equipment serving the alteration shall meet the applicable requirements of Sections 110 through 118, Section 119, and Section 150(a) through (p); and

   … (*items A through G remain the same and are omitted for brevity*)

   H. Replacements of the exterior surface of existing roofs shall meet the requirements of Section 118 and the applicable requirements of subsections i through iii where more than 50 percent of the roof or more than 1,000 square feet of roof, whichever is less, is being replaced:

   i. For Steep-sloped roofs, roofing products with a density of less than 5 pounds per square foot in climate zones 10 through 15 shall have a minimum aged solar reflectance of 0.20 and a minimum thermal emittance of 0.75, or a minimum SRI of 16.

   ii. For steep-sloped roofs, roofing products with a density of 5 pounds per square foot or more in climate zones 1 through 16 shall have a minimum aged solar reflectance of ~~0.15~~ 0.20 and a minimum thermal emittance of 0.75, or a minimum SRI of ~~10~~ 16.

   ALTERNATIVE TO SECTION 152(b)1Hi and ii: The following shall be considered equivalent to Subsection i and ii:

   a. ~~Insulation with a thermal resistance of at least 0.85 hr•ft²•°F/Btu or at least a 3/4 inch air-space is added to the roof deck over an attic; or~~

   b. Existing ducts in the attic are insulated and sealed according to Section 151(f)10; or

c. In climate zones 10, 12 and 13, with 1 ft² of free ventilation area of attic ventilation for every 150 ft² of attic floor area, and where at least 30 percent of the free ventilation area is within 2 feet vertical distance of the roof ridge; or

d. Buildings with at least ~~R-30~~ R-38 ceiling insulation; or

e. ~~Buildings with a radiant barrier in the attic meeting the requirements of Section 151(f)2; or~~

f. Buildings that have no ducts in the attic; or

g. ~~In climate zones 10, 11, 13 and 14, R-3 or greater roof deck insulation above vented attic~~.

iii. Low-sloped roofs in climate zones 13 and 15 shall have a 3-year aged solar reflectance equal or greater than ~~0.55~~ 0.67 and a thermal emittance equal or greater than 0.75, or a minimum SRI of ~~64~~ 78.

EXCEPTION to Section 152(b)1Hiii: Buildings with no ducts in the attic.

6. Bibliography and Other Research

For this measure, AEC consulted a number of research studies on cool roofing products and unvented attics. For cool roofs, AEC applied data from the Cool Roof Rating Council's product database to verify availability of high solar reflectance materials for a variety of roofing products (shingle, clay tile, concrete tile, metal roofing). The primary research for unvented attics was conducted by Building Science Corporation (BSC).

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7. Appendix A – Survey and Cost Summary Data

A series of online surveys and phone surveys were administered to the appropriate groups (builders and architects, roofing contractors, roofing manufacturers, roof truss manufacturers) to determine installed costs and typical construction practices. A summary of the results is shown below. A complete list of questions is available upon request. Individual responses have been masked to retain the confidentiality of the respondents. For roofing costs, a follow-up phone survey was conducted due to the limited response to the online survey.

7.1 Roofing Manufacturers Survey Results

7.1.1 Background

Thirteen companies responded to the survey, three of whom are located in California. Others were located in the Midwest and East Coast. The survey took approximately 10 to 15 minutes to complete, and not all respondents completed the survey. Metal roofing manufacturers were represented disproportionately, as shown in the question responses below. The majority of the respondents participate in the Cool Roof Rating Council's rating program. Most of those that participate in the CRRC program have had products' aged solar reflectance tested. About half of respondents were interested in increasing cool roofing sales. About half of respondents stated that they are currently developing new residential sloped roofing products with an initial solar reflectance (SR) of 0.25 or higher. Four respondents said that they are developing products with an initial SR of 0.40 or higher.

Q: What types of roofing products do you manufacture for the residential sloped roofing market?

Answer Options	Our biggest selling product type	Our 2nd biggest seller	Our 3rd biggest seller	We don't make this	Response Count
Asphalt Shingle	2	0	0	8	10
Metal Roofing	8	0	0	2	10
Clay Tile	0	0	0	9	9
Concrete Tile	0	0	0	9	9
Polymer Roofing	1	0	0	8	9
Other	4	1	0	4	9

Approximately 25% of their product sales are used for new construction, with the remaining 75% used for re-roofing. All of the respondents indicated that their company has sold roofing products with an initial solar reflectance of 0.25 or greater for at least one year. Four of the thirteen respondents indicated that their company has sold products with a solar reflectance of 0.25 or greater for at least ten years.

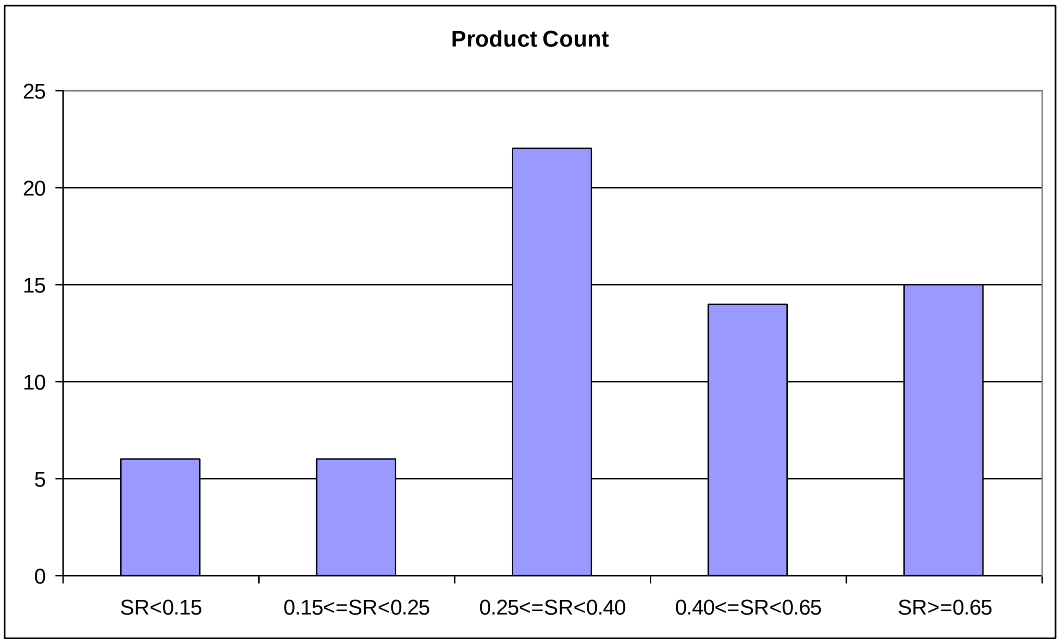
More than three-fourths of all product sales from these manufacturers comes from cool roof products. This indicates that the market for products with relatively high solar reflectance is well-established.

Q: Please estimate the percentage of your company's sales that come from materials with initial solar reflectance of 0.25 or higher.

Answer Options	Response Average
Standard Products (SR < 0.25) % of Sales:	23.83
Cool Products (SR >= 0.25) % of Sales:	76.17

Summary results to the question below (Figure 1) indicate that there are a wide variety of colors available for roofing products with initial solar reflectance between 0.25 and 0.65.

Q: How many different colors does each product line offer with initial solar reflectance (SR) falling into the following ranges?



7.1.2 Cost Data

Seven of the thirteen respondents answered the cost summary question, and of those seven, some provided only a partial answer. The survey respondents were asked to estimate roofing product costs per square and how those cost varied as roofing solar reflectance was increased. On average, roofing prices increased from $140 per square for products complying with Title 24 (SR between 0.25 and 0.40) and $167.50 per square for products with very high solar reflectance (greater than 0.65).

Number	$/Square, SR < 0.15	$/Square, 0.15 <= SR < 0.25	$/Square, 0.25 <= SR < 0.40	$/Square, 0.40 <= SR < 0.65	$/Square, SR >= 0.65
1			$135.00 / sq	$135.00 / sq	
2		0			
3			160	160	160
4		1	1.25	1.5	1.75
5	Same for all	Same for all	Same for all	Same for all	Same for all

6	SR cost us more, we don't pass on, market won't accept	SR cost us more, we don't pass on, market won't accept	SR cost us more, we don't pass on, market won't accept	SR cost us more, we don't pass on market won't accept	SR cost us more, we don’t pass on market wont accept
7					50
			140.00	148.33	167.50

Because of the limited response, and the large proportion of metal roofing manufacturers among the respondents, a separate phone survey of the major roofing manufacturers was designed to determine roofing product costs by roof type and solar reflectance. The results, shown in the table below, indicate that shingles show a significant cost premium for increasing roof solar reflectance above 0.25; however, clay and concrete tile have a negligible cost increase to go to cool roof colors. Costs are shown in $/square, and results in red indicate estimates rather than hard product costs.

Product	Low Solar reflectance	High Solar reflectance	Low cost	high cost
Shingle	0.15	0.275	50	84
30 yr shingle	0.1	0.27	70	150
50-yr shingle	0.15	0.265	97.5	170
30-yr shingle	0.15	0.28	75	95
standard process shingle	0.15	0.285	75	75
coated shingles	0.2175	0.32	80	100
Tile - std black to std white	0.05	0.2	75	75
Tile - std white to premium white 40 yr	0.2	0.28	75	105
Residential MW tile	0.13	0.68	140	141
Residential LW tile	0.13	0.68	155	156
Residential MW tile	0.29	0.53	125	125
Residential LW tile	0.33	0.51	170	170
Residential tile	0.31	0.36	170	170
tile	0.15	0.61	90	90
tile	0.4	0.82	62.5	68.5
commercial membrane	0.285	0.765	$50	$85
Torch down roofing	0.2	0.7	60	120
Roof coating	0.2	0.71	70	70
shingle	0.2	0.75	70	90

Figure 44. Roofing Product Cost Survey Summary

7.2 Roofers, Builders and Architects

A customized survey was sent to roofing contractors, builders and architects. There were seven respondents to the survey, from primarily roofing companies. Five of the seven companies who participated in the survey are located in California. On average approximately 50% of the work performed by the companies is for new homes. Two of the respondents work for large-volume home builders as shown in the table below.

Q: How many homes does your firm design, build or renovate every year?

Answer Options	Response Percent	Response Count
1 to 5	0.0%	0
6 to 10	0.0%	0
11 to 50	16.7%	1
51 to 100	0.0%	0
100 to 500	50.0%	3
more than 500	33.3%	2

Q: How much emphasis does your firm place on energy efficiency?

Answer Options	Response Percent	Response Count
We meet CA Title 24	80.0%	4
We try to exceed Title 24 by at least 10%	20.0%	1
We try to exceed Title 24 by at least 20%	0.0%	0
Our houses routinely achieve LEED ratings	0.0%	0
We are trying to build "zero-energy" homes	0.0%	0

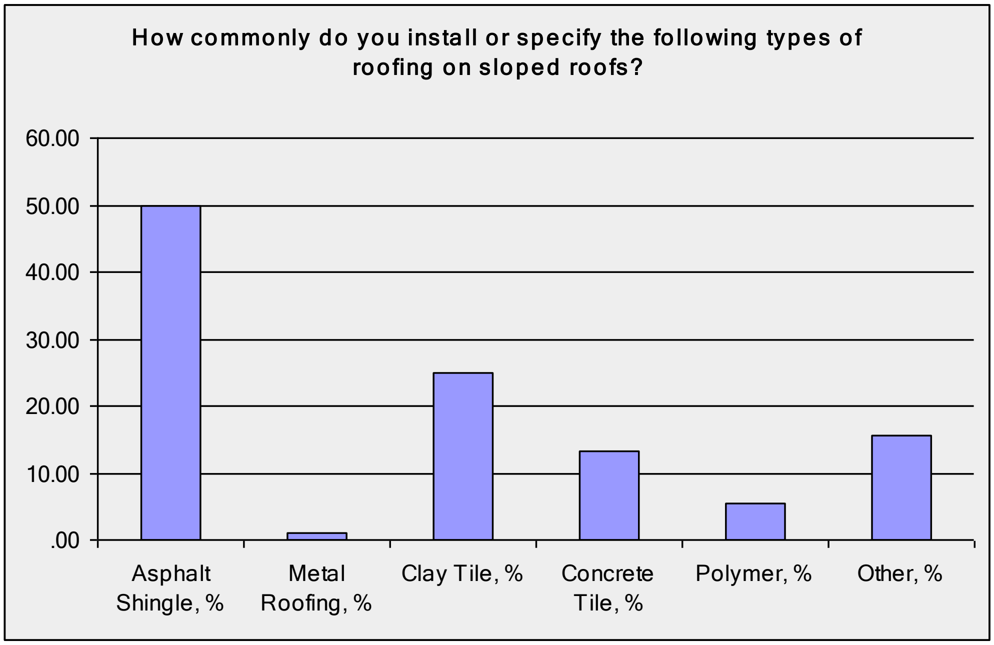
Cool roof materials, improved roof insulation, more efficient windows and doors and better duct insulation and sealing are the most common energy efficiency strategies employed by the respondents.

Q: What strategies does your firm use to increase the efficiency of homes? (check all that apply...)

Answer Options	Response Percent	Response Count
None	0.0%	0
Better wall insulation	0.0%	0
Better roof insulation	80.0%	4
Cool roof materials	100.0%	5
Better envelope sealing	20.0%	1
More efficient windows & doors	40.0%	2
Innovative envelope design (straw bale, structural insulated panels, etc.)	0.0%	0
More efficient heating & cooling equipment	0.0%	0
Better duct insulation & sealing	40.0%	2
Locating ducts in conditioned space	0.0%	0
Innovative HVAC system design (ground source heating or cooling, evaporative cooling, etc.)	0.0%	0
Efficient solar design to minimize cooling & maximize heating	40.0%	2
More efficient lighting systems	20.0%	1
Better control systems	0.0%	0
Other...	0.0%	0

7.3 Roofing Survey Responses

The most common roofing type for sloped roofs is asphalt shingle and clay tile; however not all survey participants responded to this question.



The survey revealed that none of the roofers or builders choose white as a roof color.

Q: What colors do you choose for each of your common brand choices? (you can pick more than one!)

Answer Options	Black	Gray	Tan/Brown	Red/TerraCotta	Green	Blue	White	Metallic
Brand 1:	1	3	2	1	1	1	0	0
Brand 2:	1	1	3	1	0	0	0	0
Brand 3:	0	0	0	1	1	0	0	0
Brand 4:	1	0	0	0	0	0	0	0
Brand 5:	0	0	1	0	0	0	0	0

Most of the products installed fall into the solar reflectance range of 0.25 to 0.40. Some fall below 0.25.

Q: What range does the solar reflectance of the brands & colors you choose fall into? (SR below means solar reflectance)

Answer Options	SR not specified/don't know	Standard materials, SR < 0.25	Cool materials, 0.25 <= SR < 0.40	Cooler materials, 0.40 <= SR < 0.65	Coolest materials, SR >= 0.65
Brand 1:	1	1	2	1	0
Brand 2:	1	1	2	0	0
Brand 3:	1	2	0	0	0
Brand 4:	2	0	0	0	0
Brand 5:	1	0	0	0	0

7.3.1 Cost Data

Incremental cost data for products with high solar reflectance is difficult to determine from the survey responses. Only three of the seven respondents for this survey indicated incremental cost data and the results were widely scattered. A separate phone survey was conducted to determine incremental costs for high solar reflectance products.

7.4 Raised Heel Truss

One of the respondents stated that they use a raised heel truss 10% of the time. One respondent stated that they use rigid insulation for mountain climate zones. No other information was provided by this group on raised heel trusses.

7.4.1 Roof Insulation

Q: What types of insulation do you use for cathedral ceilings?

Answer Options	Never	10%	25%	50%	75%	90%	Always
None	1	0	0	0	0	0	1
Rigid insulation	1	0	0	1	0	0	1
Rigid insulation with foil backing	0	0	0	0	0	1	0
Fiberglass batt	0	0	0	0	0	0	1
Cellulose or cotton batt	0	0	0	0	0	0	0
Spray foam	0	0	0	1	0	0	1
Radiant barrier	0	1	0	0	0	0	0
Other	0	0	0	0	0	0	0

Q: What do you consider to be the potential benefits and drawbacks of an unvented attic?
Responses:
Unvented attics increase vapor and heat during the summer months.
hotter roof shingle temperatures, moisture control issues

7.4.2 Raised Heel Truss Responses

Approximately twenty residential truss manufacturers were surveyed to determine the incremental cost of a raised heel truss. Only six manufacturers responded to the survey. Incremental costs ranged between 2% and 10% of the cost of a standard truss. Some manufacturers indicated that structural blocking might require additional costs, when the raised heel reaches a height of 12” or higher.
In addition to the truss manufacturers, home builders were surveyed using the phone survey above. Most of the respondents did not use raised heel trusses. One said that they could negotiate a price for a raised heel truss that is virtually equivalent to the cost of a standard truss, due to market conditions.

	Min	Max	Avg	Notes
Percentage residential trusses	80%	95%	86%	

Percentage commercial trusses	5%	20%	14%	
Percentage new homes	50%	95%	81%	
Percentage existing homes	5%	50%	19%	
Number of homes	100	3000	1460	
Does firm construct raised heel trusses	No	Yes, but only a handful	Yes, but only a handful	
Incremental Cost of raised heel trusses	2%	10%	7.25%	Blocking can add $200 to the cost if the heel exceeds 10-12"; other manuf. says 6% for std. heel, 10% for high heel
Typical heel height	8 in.	12 in.	10.25 in.	

Figure 45. Raised Heel Truss Survey Results

The raised heel truss carries an incremental cost of 7% over the standard truss price of $3.50 per square foot of projected area. The standard truss cost of $3.50/ft^2 of projected roof area is derived from a phone survey and RS Means 2010 Building and Construction Cost Data. If blocking is needed (typical for trusses with heights of 12 inches or more), then the incremental cost goes to 9%.

8. Appendix B: Compliance Options

As part of this analysis, two compliance options were considered as alternatives to the vented attic package: a high solar reflectance cool roof package and an unvented attic package. The intent of these options is to give the designers greater flexibility in meeting the prescriptive standards. Since the vented attic package has been shown to be cost effective, the cost effectiveness of the compliance options does not need to be proven. Instead, the compliance options are designed to use no more TDV energy than the vented attic package, for each climate zone.

8.1 High Solar Reflectance Cool Roof

A higher solar reflectance cool roof was considered as a compliance option, as an alternative to the roof deck insulation requirement. This compliance option would include a higher solar reflectance than the vented attic package, and would include a raised heel truss in climate zones 11 to 16, but would not include the below deck insulation. Since this would not be a code requirement, cost effectiveness need not be proven. The roof solar reflectance was calculated that would provide the same TDV energy savings as the vented attic package. For most climate zones, the roof solar reflectance required to achieve this energy equivalence would exceed 0.70 in several climate zones.

The results in the tables below show the required solar reflectance that would be needed to provide the same energy benefit of R-13 insulation directly below the roof deck with 0.24 solar reflectance. This analysis assumes the use of a radiant barrier and a raised heel truss. In most cases a high solar reflectance (0.55 to 0.7 or higher) is required to achieve the same savings as installing insulation below the roof deck.

Climate Zone	kTDV/ft^2 (sr 0.1)	kTDV/ft^2 (sr0.24)	kTDV/ft^2 (sr 0.4)	kTDV/ft^2 (sr 0.7)	*sr for Equivalent TDV energy Use*
1	45.25	45.81	46.54	48.59	*0.15*
2	55.87	55.06	54.14	52.25	*n/a*
3	37.46	37.25	37.05	36.75	*n/a*
4	57.01	55.92	54.62	51.44	*0.78*
5	37.38	37.98	38.73	40.9	*0.15*
6	38.26	37.48	36.67	34.76	*0.72*
7	30.06	29.38	28.59	26.83	*0.54*
8	52.72	51.19	49.34	44.63	*0.58*
9	75.28	75.28	71.65	66.32	*0.63*
10	82.03	82.03	77.18	70.6	*0.64*
11	123.46	123.46	118.02	110.09	*0.72*
12	86.95	86.95	82.36	75.6	*0.69*
13	121.9	121.9	116.21	107.7	*0.72*
14	111.66	111.66	106.76	100.13	*0.72*
15	162.57	162.57	155.22	144.45	*0.66*
16	*93.03*	*93.03*	*90.37*	*86.76*	*0.82*

Figure 46. Equivalent Roof Solar Reflectance (sr) for Compliance Option.

For climate zones 2 and 3, no amount of solar reflectance yielded an equivalent energy use as the vented attic package that includes below deck insulation.

Since a residential roof solar reflectance of 0.7 is not practical in the residential market, we considered a modest increase in roof solar reflectance as part of the vented attic package. An increase in required reflectance to 0.24, regardless of roof mass, would be readily achievable for most types of roofing products (shingle, tile, metal roofing).

8.2 Unvented Attics

As a compliance option, and possible path towards complying with the Reach Code, an unvented (fully sealed) attic was analyzed. For this option, all insulation is placed directly at the roof deck and all openings and vents in the attic are sealed. This greatly reduces conductive and radiative heat loss to and from the attic duct work and mitigates the effects of duct leakage.

Compliance software that can fully model unvented attics was not available at the time of the initial investigation; however, some modeling of cathedralized attics was performed to evaluate ducts in conditioned space as a possible measure. The ducts in conditioned space can be done with an unvented attic or vented attic. The International Residential Code requires a 1” air space between the top of the roof insulation and the roof deck; however it does allow for exceptions. See section 4.4 for more details.

9. Appendix C: U-factor Derating Procedure

For the raised heel truss measure, we are required to estimate the effect that insulation compression has on the U-factor. The current published U-factors in Reference Appendix JA4 assume that the insulation is compressed over only a small fraction of the roof area (7.25%). In practice, the insulation may be compressed over a far greater area. For this calculation for the initial April 2011 stakeholder meeting, we used a modified form of the parallel path method.

A spreadsheet was developed that required only the following inputs:
1. Roof pitch (i.e. 4 in 12)
2. Roof gross area dimensions (i.e. 40 ft x 30 ft)
3. Attic nominal insulation level (i.e., R-38)

			Roof Pitch				Roof Area	
			height	length		length	Width	total Area
			4	12		50	29	1450
Nominal R-Value	assumed R-Value in the Roof	U-factor	insulation depth in.	Length not insulated to the full height (feet)		Area covering		Precent of total areaa
38	max	0.0243	10.270	2.57		1070.69		73.84
						Area covering		
25.5	avg.	0.0349	6.760	1.69		277.81		19.16
						Area covering		
13	R-13	0.0607	3.25	0.81		101.50		7.00
				Area Weighted average	Equivalent	R-value		
				0.0288751	34.632			

Figure 47. Screen Shot of Parallel Path Spreadsheet Tool

The fields in orange and green are calculated values. The area for the second row (“Area covering”), compressed insulation, is calculated based on the roof geometry and depth of insulation. The area of the third row, the framing, is determined from a framing factor of 0.07 for framing that is 24” on center (o.c.). The area where full insulation is assumed is the remaining area.

Framing Factor
0.07

The yellow cells are inputs that can be modified by the user. Once the procedure is finalized, columns will be added to show intermediate steps more clearly.

Ins	Roof R-value	Framing	Total Section R-Value	U-factor
38	3.16	0	41.16	0.0243
25.5	3.16	0	28.66	0.0349
13	0	3.47	16.47	0.0607

Intermediate calculations are shown above. For the roof area with full insulation, the R-38 attic insulation is added to an R-value of 3.16 for the roof assembly, which includes exterior air film, asphalt shingle, building paper, half-inch plywood, an air gap, half-inch gypsum and an interior air film. The second row refers to the area where insulation is compressed; for this section, the insulation level is assumed to be (on average) at half-depth. The third row corresponds to the minimum insulation level at the eaves and the R-value of the framing. A framing factor of 0.07 is assumed for framing 24" o.c.

Once the effective R-value and U-factor for each of the three sections is determined, the assembly U-factor is calculated as a weighted average of the three sections.

After the April 11 workshop, we decided to use a two-dimensional heat transfer program to estimate the U-factor, to account for horizontal heat flow that occurs at the eaves. The parallel path method is only valid for estimating one-dimensional heat flow, such as through a wall stud and cavity insulation assembly. The two-dimensional heat transfer model uses a finite element program, FEHT, and this work was conducted with Bruce Wilcox. The 2D heat transfer approach resulted in slightly less derating of U-factor (increase in values) due to insulation compression.

10. Appendix D: Prototype Summary

The prototype used in the cost effectiveness calculations is based on the 2,700 ft^2 prototype house defined Title 24 life-cycle cost methodology report, with the following modifications:

1. Both asphalt shingle and tile roof were tested, by varying the roof mass from light to heavy. The tile roof assembly in MICROPAS also includes an R-value of 0.85 above the roof deck to simulate the effect of the air gap between the roof deck and tile.
2. The roof pitch was set to 4 in 12 for both the asphalt shingle and tile cases. (The default prototype included with MICROPAS used a 5 and 12 roof pitch.)
3. For the integrated analysis, custom values for the U-factor for the R-30 attic insulation case and R-38 attic insulation case were used, to better account for the effect of insulation compression near the eaves. The U-factors shown in the table below were used, instead of the Reference Appendix JA4 assembly values.

Revised values for calculating the effect of a raised heel truss are based on the following updated results of the 2D finite element heat transfer analysis:

Ceiling R Value	JA4 Value (16” o.c.)	Overall Standard	Raised Heel Truss	Change in U-factor
R-30	0.0320	0.0326	0.0313	0.0013
R-38	0.0260	0.0276	0.0255	0.0021
R-60	0.0170	0.0211	0.0178	0.0033

Figure 48. Calculated results from the finite element heat transfer analysis

The change in U-factor due to de-rating is directly proportional to the energy savings estimate from a raised heel truss, since there is a linear correlation of TDV energy use with U-factor.

All other building attributes were set to be in exact compliance with the 2008 Standards and prescriptive requirements.

11. Appendix E: Follow-up Phone Survey

A survey developed for production home builders and architects was sent to approximately 80 recipients. Approximately one-quarter of the recipients opened the email, but only two participated in the survey. It may be difficult to find the right contact at large corporations that have the time, willingness and knowledge to complete the survey.

As a follow-up, select phone calls were made to some of the production home builders to answer a few questions key to our study. The following abbreviated phone survey was developed.

1. Have you ever used raised-heel trusses on production homes in California?
    a. If so, what is the fraction of homes that use a raised heel truss?
    b. What area(s) of California are they used?
    c. What is the typical height of the raised heel truss?
    d. What is the additional cost in dollars of a raised heel truss? (include additional siding)
2. What is the most common roofing type for new homes (asphalt shingle, clay tile, concrete tile, other)? What percentage of new homes use tile roofs? (If possible get an approximate % breakdown for shingle, tile, metal, other)
3. For the most common roof types, what is the common (initial) solar reflectance of the products you use?
4. How do you typically insulate cathedral ceilings?
5. How often is ductwork located in the attic? (Do you build homes with all ducts in conditioned space?)
6. Have you built any homes with unvented attics?
7. What do you consider to be the benefits and drawbacks of an unvented attic?

12. Appendix F: Statewide Construction Forecast

The Residential construction forecast dataset is data that is published by the California Energy Commission's (CEC) demand forecast office. This demand forecast office is charged with calculating the required electricity and natural gas supply centers that need to be built in order to meet the new construction utility loads. Data is sourced from the California Department of Finance and California Construction Industry Research Board (CIRB) building permits. The Department of Finance uses census years as independent data and interpolates the intermediate years using CIRB permits. CASE stakeholders expressed concern that the Residential forecast was inaccurate compared with other available data (in 2010 CEC forecast estimate is 97,610 new units for single family and the CIRB estimate is 25,526 new units). In response to this discrepancy, HMG revised the CEC construction forecast estimates. The CIRB data projects an upward trend in construction activity for 2010-2011 and again from 2011-2012. HMG used the improvement from 2011-2012 and extrapolated the trend out to 2014. The improvement from 2011-2012 is projected to be 37%. Instead of using the percent improvement year on year to generate the 2014 estimate, HMG used the conservative value of the total units projected to be built in 2011-2012 and added this total to each subsequent year. This is the more conservative estimate and is appropriate for the statewide savings estimates. Based on this trend, the new construction activity is on pace to regain all ground lost by the recession by 2021. The multi-family construction forecasts are consistent between CEC and CIRB and no changes were made to the multi-family data.

Residential New Construction Estimate (2014)			
	Single Family	Multi-family Low Rise	Multi-family High Rise
CZ 1	378	94	-
CZ 2	1,175	684	140
CZ 3	1,224	863	1,408
CZ 4	2,688	616	1,583
CZ 5	522	269	158
CZ 6	1,188	1,252	1,593
CZ 7	2,158	1,912	1,029
CZ 8	1,966	1,629	2,249
CZ 9	2,269	1,986	2,633
CZ 10	8,848	2,645	1,029
CZ 11	3,228	820	81
CZ 12	9,777	2,165	1,701
CZ 13	6,917	1,755	239
CZ 14	1,639	726	-
CZ 15	1,925	748	-
CZ 16	1,500	583	-
Total	47,400	18,748	13,845

Figure 49. Residential construction forecast for 2014, in total dwelling units

The demand generation office publishes this dataset and categorizes the data by demand forecast climate zones (FCZ). These 16 climate zones are organized by the generation facility locations throughout California, and differ from the Title 24 building climate zones (BCZ). HMG has reorganized the demand forecast office data using 2000 Census data (population weighted by zip code) and mapped FCZ and BCZ to a given zip code. The construction forecast data is provided to CASE authors in BCZ in order to calculate Title 24 statewide energy savings impacts. Though the individual climate zone categories differ between the demand forecast published by the CEC and the construction forecast, the total construction estimates are consistent; in other words, HMG has not added to or subtracted from total construction area.

The demand forecast office provides two (2) independent data sets: total construction and decay rate. Total construction is the sum of all existing dwelling units in a given category (Single family, Multi-family low rise and Multi-family high rise). Decay rate is the number of units that were assumed to be retrofitted, renovated or demolished. The difference in total construction between consecutive years (including each year's decay rate) approximates the new construction estimate for a given year.

In order to further specify the construction forecast for the purpose of statewide energy savings calculation for Title 24 compliance, HMG has segmented all multi-family buildings into low rise and high rise space (where high rise is defined as buildings 4 stories and higher). This calculation is based on data collected by HMG through program implementation over the past 10 years. Though this sample is relatively small (711), it is the best available source of data to calculate the relative population of high rise and low rise units in a given FCZ.

Most years show close alignment between CIRB and CEC total construction estimates, however the CEC demand forecast models are a long-term projection of utility demand. The main purpose of the CEC demand forecast is to estimate electricity and natural gas needs in 2022, and this dataset is much less concerned about the inaccuracy at 12 or 24 month timeframe.

It is appropriate to use the CEC demand forecast construction data as an estimate of future years construction (over the life of the measure), however to estimate next year's construction, CIRB is a more reliable data set.

Citation

"Res Construction Forecast by BCZ v4"; Developed by Heschong Mahone Group with data sourced September, 2010 from Sharp, Gary at the California Energy Commission (CEC)